

Running Jobs on Expanse (a practical guide)

October 8, 2020

Mary Thomas
mthomas@sdsc.edu

EXPANSE
COMPUTING WITHOUT BOUNDARIES

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage, Globus Endpoints, Data Movers, Mount Points
- Final Comments

Basic Information

- Expanse User Guide:
 - https://www.sdsc.edu/support/user_guides/expanse.html
- Online repo for this webinar:
 - https://github.com/sdsc-hpc-training/webinars/tree/master/202004_expanse_101
- Basic Skills:
 - You must be familiar with running basic Unix commands, connecting to Expanse via SSH, running notebooks, and other basic skills. See:
 - https://github.com/sdsc-hpc-training-org/basic_skills
- You need to have an Expanse account in order to access the system. There are two ways to do this:
 - Submit a proposal through the [XSEDE Allocation Request System](#)
 - Request a trial account @ <https://portal.xsede.org/allocations/startup>.

SDSC HPC Training

- SDSC Training Events:
 - https://www.sdsc.edu/education_and_training/training.html
- HPC Training GitHub repository:
 - View interactive videos, download talks, code, etc.
 - <https://github.com/sdsc-training-org>
 - <https://education.sdsc.edu/training/interactive>
- Upcoming Expanse Training:
 - Comet to Expanse Transition Workshop, Thursday 10/29/2020, 11am-2:30pm PDT. See:
 - https://www.sdsc.edu/event_items/XXXXXXX
 - Running Jupyter Notebooks on Expanse, Thursday, 12/10/2020, 11am. See:
 - https://www.sdsc.edu/event_items/XXXXXXX

Outline

- **Expanse Overview & Innovative Features**
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

EXPANSE

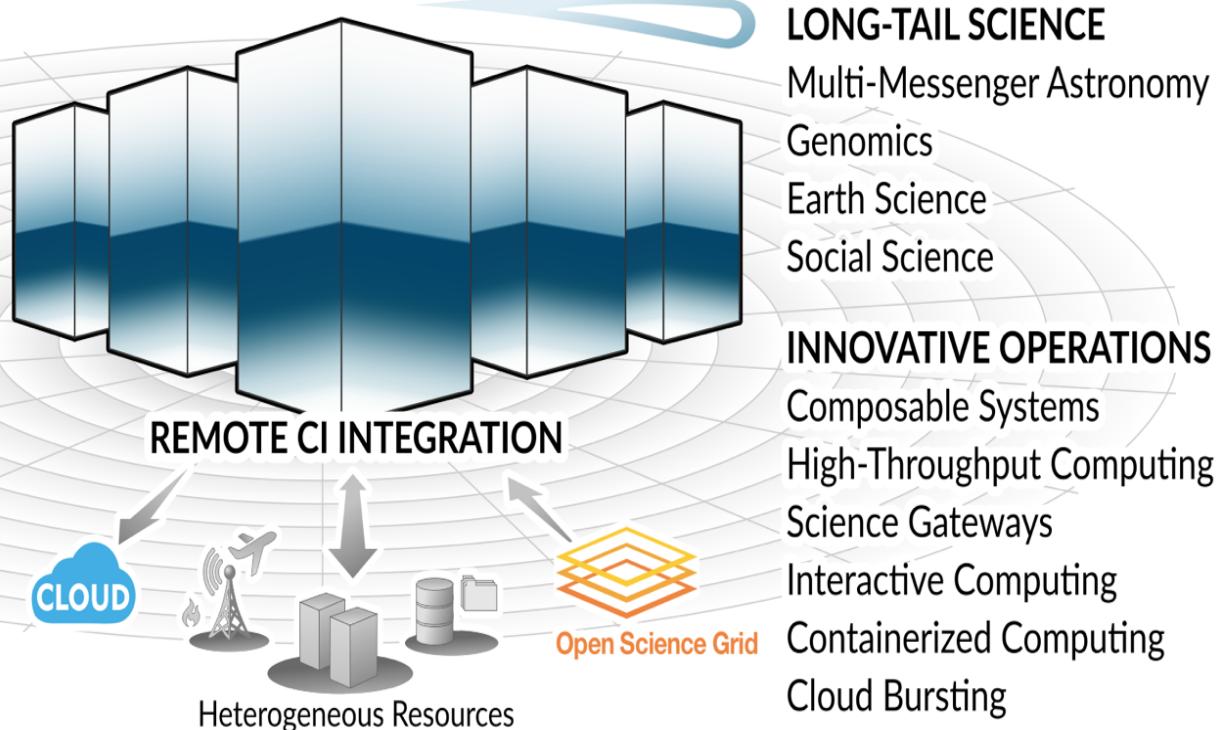
COMPUTING WITHOUT BOUNDARIES
5 PETAFLOP/S HPC and DATA RESOURCE

HPC RESOURCE

13 Scalable Compute Units
728 Standard Compute Nodes
52 GPU Nodes: 208 GPUs
4 Large Memory Nodes

DATA CENTRIC ARCHITECTURE

12PB Perf. Storage: 140GB/s, 200k IOPS
Fast I/O Node-Local NVMe Storage
7PB Ceph Object Storage
High-Performance R&E Networking

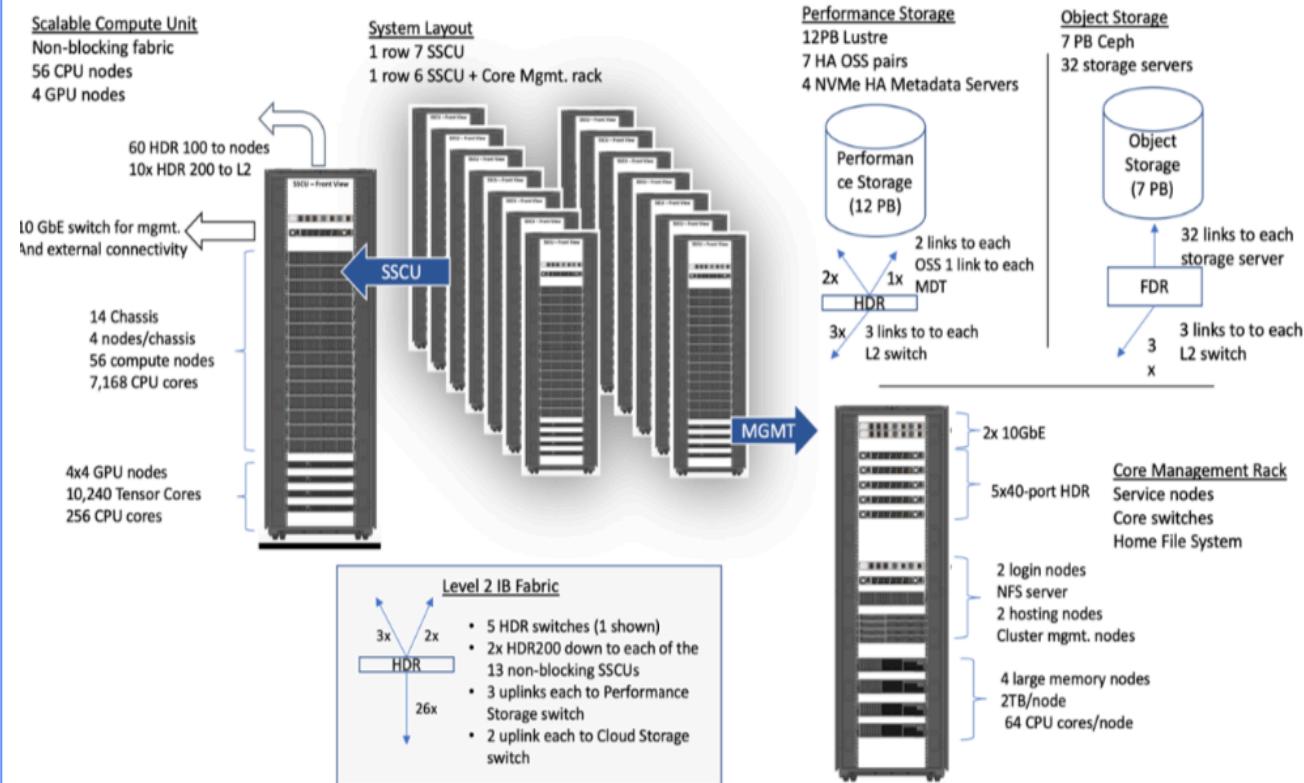


For more details see the Expanse user guide @ https://www.sdsc.edu/support/user_guides/expanse.html
and the "Introduction to Expanse" webinar @ https://www.sdsc.edu/event_items/202006_Introduction_to_Expanse.html

Expanse Heterogeneous Architecture

System Summary

- 13 SDSC Scalable Compute Units (SSCU)
- 728 x 2s Standard Compute Nodes
- 93,184 Compute Cores
- 200 TB DDR4 Memory
- 52x 4-way GPU Nodes w/NVLINK
- 208 V100s
- 4x 2TB Large Memory Nodes
- HDR 100 non-blocking Fabric
- 12 PB Lustre High Performance Storage
- 7 PB Ceph Object Storage
- 1.2 PB on-node NVMe
- Dell EMC PowerEdge
- Direct Liquid Cooled



SCCU

The SCCU is Designed for the Long Tail Job Mix, Maximum Performance, Efficient Systems Support, and Efficient Power and Cooling

Standard Compute Nodes

- 2x AMD EPYC 7742 @2.25 GHz
- 128 Zen2 CPU cores
- PCIe Gen4
- 256 GB DDR4
- 1.6 TB NVMe

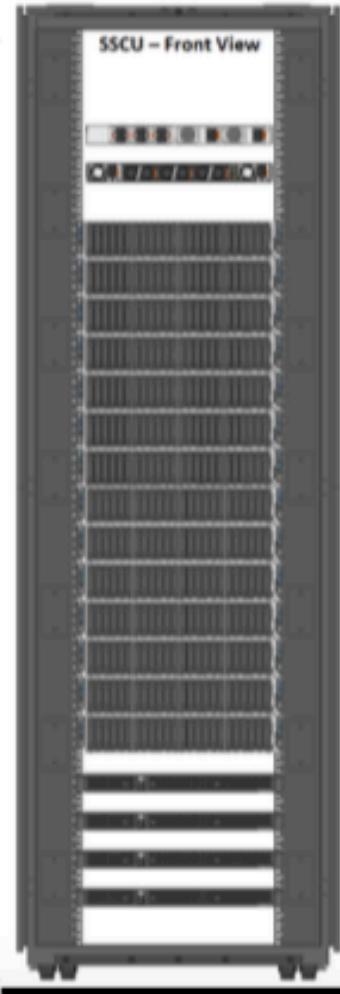
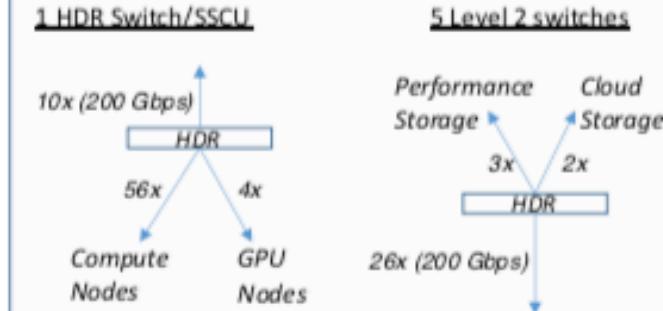
GPU Nodes

- 4x NVIDIA V100/follow-on
- 10,240 Tensor Cores
- 32 GB GDDR
- 1.6 TB NVMe
- Intel CPUs

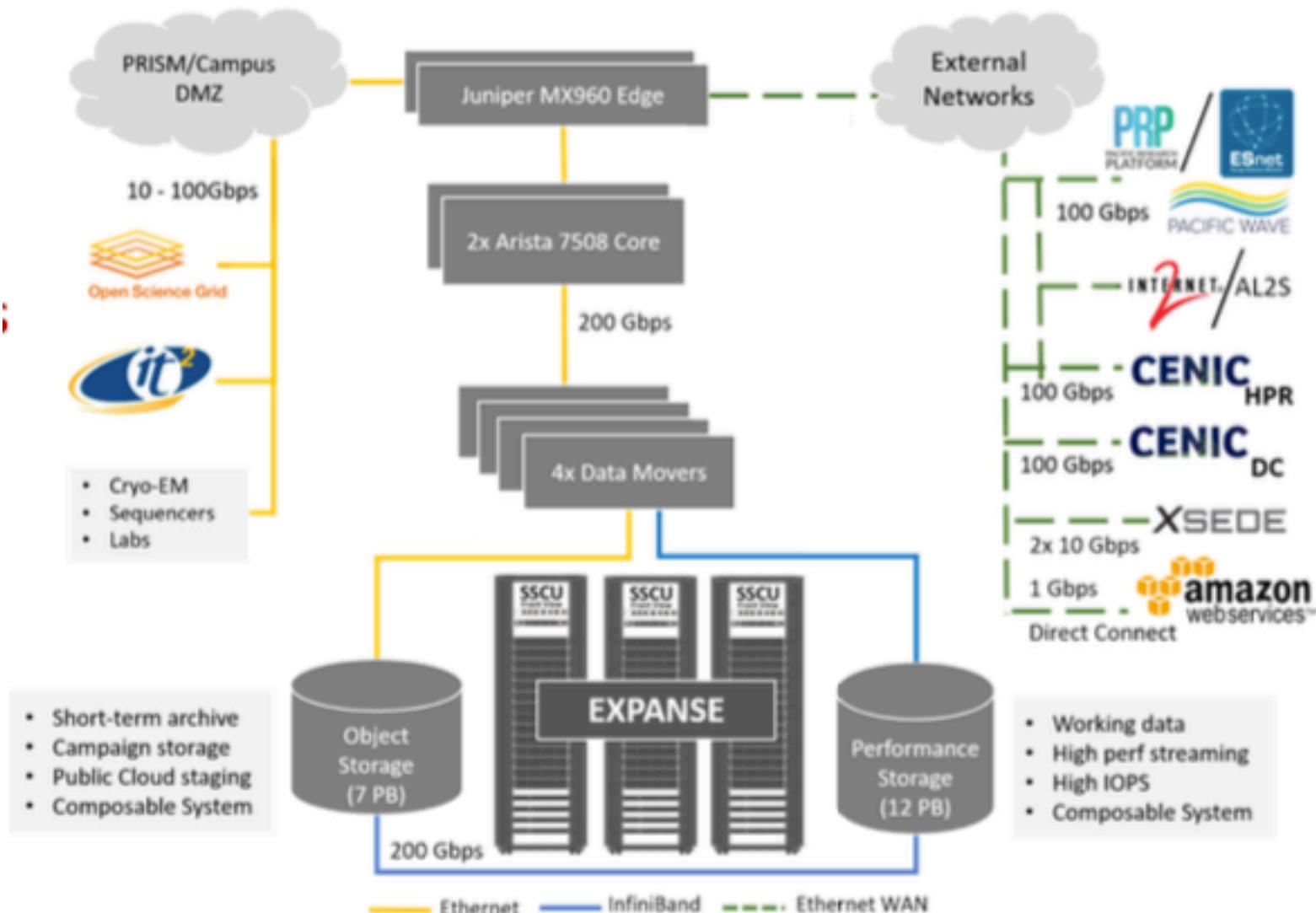
SCCU Components

- 56x CPU nodes
- 7,168 Compute Cores
- 4x GPU nodes
- 1x HDR Switch
- 1x 10GbE Switch
- HDR 100 non-blocking fabric
- Wide rack for serviceability
- Direct Liquid Cooling to CPU nodes

Non-blocking Interconnect



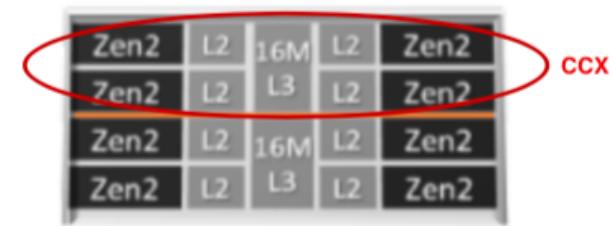
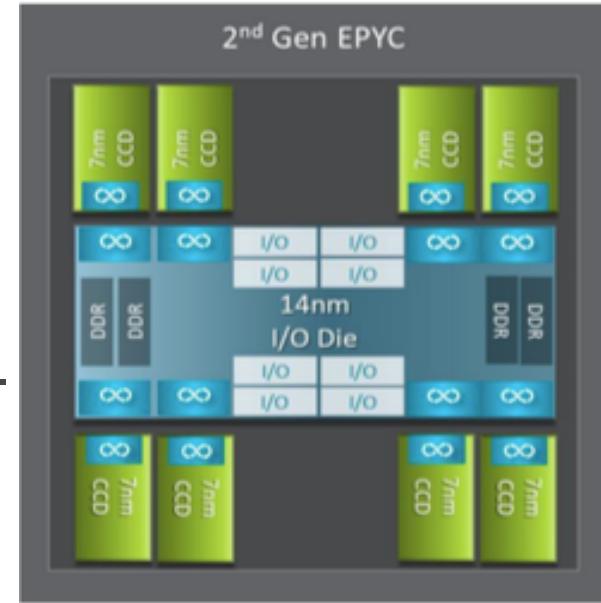
Expanse Connectivity Fabric



Facilitates Compute and Data Workflows

AMD EPYC 7742 Processor Architecture

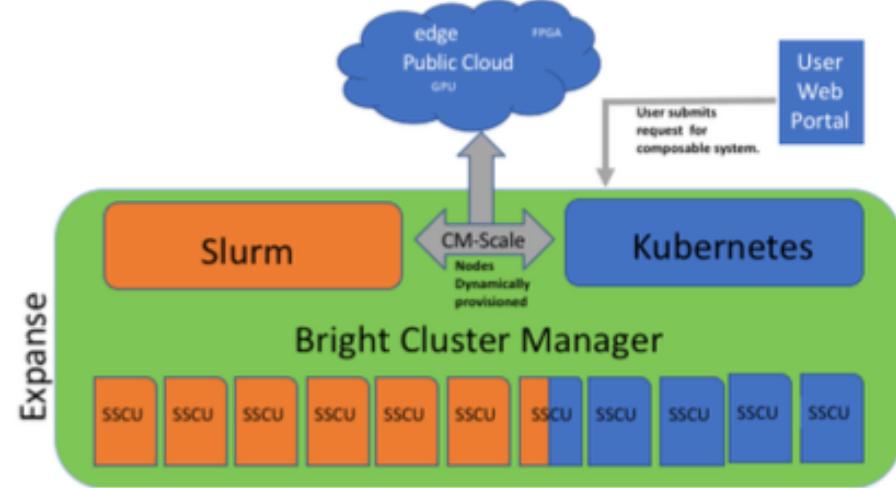
- 8 Core Complex Dies (CCDs).
- CCDs connect to memory, I/O, and each other through the I/O Die.
- 8 memory channels per socket.
- DDR4 memory at 3200MHz.
- PCI Gen4, up to 128 lanes of high speed I/O.
- Memory and I/O can be abstracted into separate quadrants each with 2 DIMM channels and 32 I/O lanes.
- 2 Core Complexes (CCXs) per CCD
- 4 Zen2 cores in each CCX share a16ML3 cache. Total of $16 \times 16 = 256$ MB L3 cache.
- Each core includes a private 512KB L2 cache.



→ EPYC Architecture has impact on compiling and batch script configuration

Composable Systems will support complex, distributed, workflows – making Expanse part of a larger CI ecosystem

- Bright Cluster Manager + Kubernetes
- Core components developed via NSF- funded CHASE-CI (NSF Award # 1730158), and the Pacific Research Platform (NSF Award # 1541349)
- Requests for a composable system will be part of an XRAC request
- Advanced User Support resources available to assist with projects - **this is part of our operations funding.**



Integration with Public Cloud *

- Supports projects that share data, need access to novel technologies, and integrate cloud resources into workflows
- Slurm + in-house developed software + Terraform (Hashicorp)
- Early work funded internally and via NSF E-CAS/Internet2 project for CIPRES (Exploring Cloud for the Acceleration of Science, Award #1904444).
- Approach is cloud-agnostic and will support the major cloud providers.
- Users submit directly via Slurm, or as part of a composed system.
- Options for data movement: data in the cloud; remote mounting of file systems; cached filesystems (e.g., StashCache), and data transfer during the job.
- Training Events Planned for early 2021

* Funding for user cloud resources is not part of the Expanse award. Researcher must have access to these via other NSF awards and funding.

Expanse Status

- A beautiful work in progress.
- Currently in early user phase, so many of the system features and services are still being tested.
 - Expanse will move into production on 11/1/2020
 - Comet will conclude operations in March 2021.
- New accounts -- Warning
 - When you get your account, you will not inherit any of your Comet environment, directories, scripts, etc.
 - Need help? Come to the transition workshop:
 - https://www.sdsc.edu/event_items/202010_Comet_to_Expanse_TransitionTutorial.html

Outline

- Expanse Overview & Innovative Features
- **Getting Started**
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

Logging into Expanse

- Expanse supports Single Sign-On through the XSEDE User Portal
- From the command line using an XSEDE-wide password,
 - Coming soon the Expanse User Portal.
- CPU and GPU resources are allocated separately, the login nodes are the same.
- To log in to Expanse from the command line, use the hostname:
 - `login.expanse.sdsc.edu`
- Secure shell (SSH) command examples:

```
ssh <your_username>@login.expanse.sdsc.edu
```

```
ssh -l <your_username> login.expanse.sdsc.edu
```

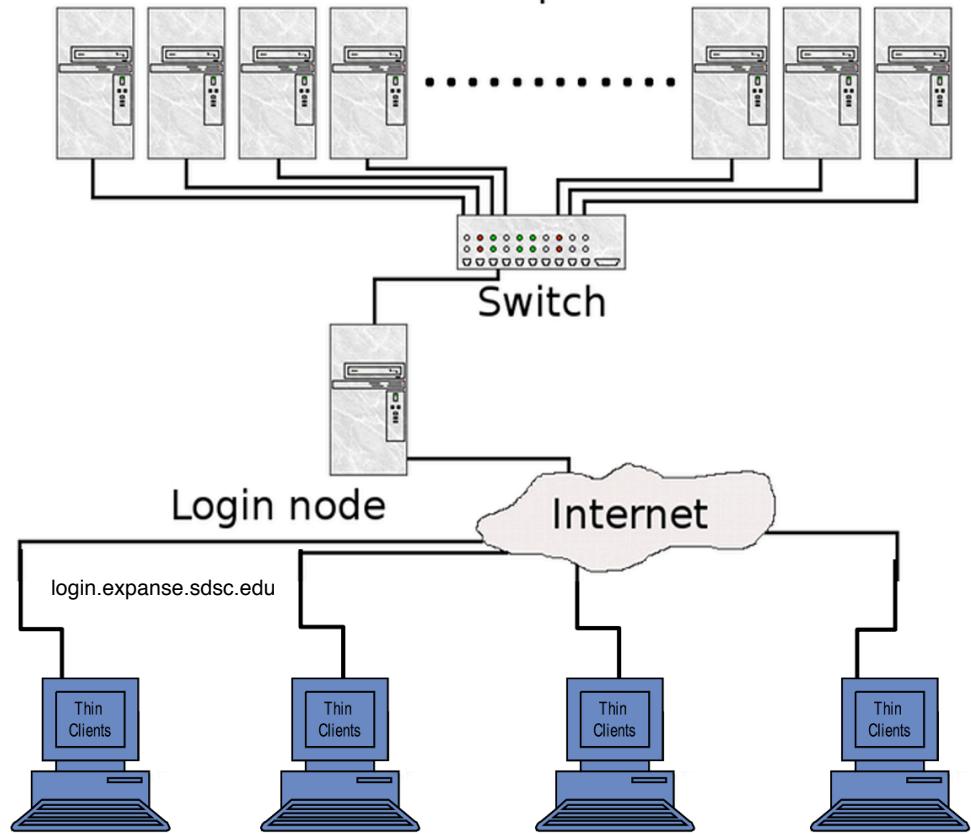
- When you log in to `login.expanse.sdsc.edu`, you will be assigned one of the two login nodes `login0[1-2]-expanse.sdsc.edu`. Both systems are identical.

Using SSH Keys

- You can append your public key (e.g. from your laptop) to your `~/.ssh/authorized_keys` file to enable access from authorized hosts without having to enter your password.
- RSA, ECDSA and ed25519 keys are accepted.
- Make sure you have a **strong passphrase** on the private key on your local machine.
- You can use ssh-agent or keychain to avoid repeatedly typing the private key password.
- Hosts which connect to SSH more frequently than ten times per minute may get blocked for a short period of time
- See the SDSC Security Webinar:
 - https://www.sdsc.edu/event_items/202007_CometWebinar.html

System Access: Clients

- Linux/Mac –
 - use terminal + installed ssh app
- Windows:
 - Win10 terminal app + installed ssh app
 - Older Windows OS's: ssh clients apps Putty, Cygwin
- Login hostname for SDSC Expanse:
 - login.expanse.sdsc.edu
 - 198.202.113.252



SDSC tutorial on HPC security: https://www.sdsc.edu/event_items/202007_CometWebinar.html

Example of a terminal connection:

```
(base) quantum:~ mthomas$ ssh -l mthomas login.expanse.sdsc.edu
Last login: Wed Oct  7 11:04:17 2020 from 76.176.117.51
[mthomas@login02 ~]$
[mthomas@login02 ~]$
[mthomas@login02 ~]$ whoami
mthomas
[mthomas@login02 ~]$
[mthomas@login02 ~]$ pwd
/home/mthomas
[mthomas@login02 ~]$
[mthomas@login02 ~]$
```

Typically you would also see a logon message – often called the MOTD (message of the day, located in /etc/motd). This has not been implemented at this point on Expanse

Obtaining Tutorial Example Code

- We will be using the example code from GitHub repository located here:
 - <https://github.com/sdsc-hpc-training-org/expanse-101>
- The example below will be for anonymous HTTPS downloads

```
[mthomas@login01 ~]$ mkdir hpctrain
[mthomas@login01 ~]$ cd hpctrain/
[mthomas@login01 hpctrain]$ git clone https://github.com/sdsc-hpc-training-org/expanse-101.git
Cloning into 'expanse-101'...
remote: Enumerating objects: 49, done.
remote: Counting objects: 100% (49/49), done.
remote: Compressing objects: 100% (44/44), done.
remote: Total 49 (delta 8), reused 40 (delta 4), pack-reused 0
Unpacking objects: 100% (49/49), done.
[mthomas@login01 hpctrain]$ ls -al
total 36
drwxr-xr-x 3 mthomas use300 3 Oct  7 14:15 .
drwxr-x--- 8 mthomas use300 20 Oct  7 14:14 ..
drwxr-xr-x 5 mthomas use300  8 Oct  7 14:15 expanse-101
[mthomas@login01 hpctrain]$ cd expanse-101
drwxr-xr-x 5 mthomas use300  8 Oct  7 14:15 .
drwxr-xr-x 3 mthomas use300  3 Oct  7 14:15 ..
drwxr-xr-x 6 mthomas use300  6 Oct  7 14:15 examples

drwxr-xr-x 8 mthomas use300 13 Oct  7 14:15 .git
-rw-r--r-- 1 mthomas use300 460 Oct  7 14:15 .gitignore
drwxr-xr-x 2 mthomas use300 10 Oct  7 14:15 images
-rw-r--r-- 1 mthomas use300 907 Oct  7 14:15 README.md
-rw-r--r-- 1 mthomas use300 77199 Oct  7 14:15 running_jobs_on_expanse.md
```

Obtaining Tutorial Example Code

Remember to make a copy of the code you decide to work on to simplify recovering when you have an error or make a mistake.

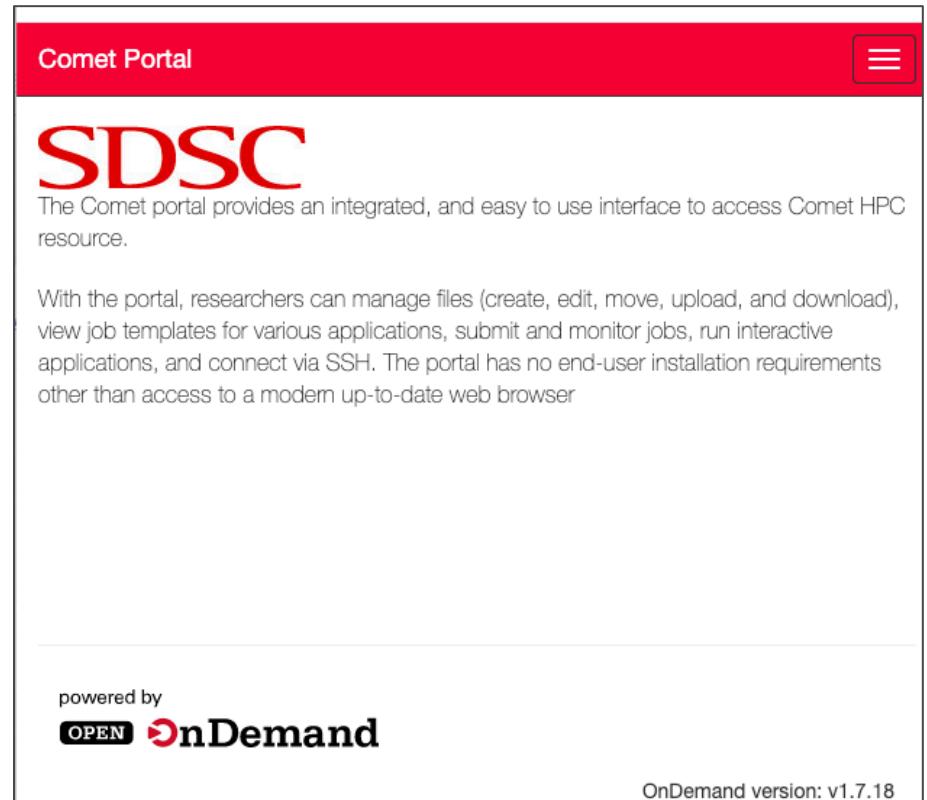
```
[mthomas@login01 expanse-101]$  
[mthomas@login01 expanse-101]$ cd examples/  
[mthomas@login01 examples]$ ls -al  
total 88  
drwxr-xr-x 6 mthomas use300 6 Oct 7 14:15 .  
drwxr-xr-x 5 mthomas use300 8 Oct 7 14:15 ..  
drwxr-xr-x 2 mthomas use300 6 Oct 7 14:15 HYBRID  
drwxr-xr-x 2 mthomas use300 6 Oct 7 14:15 MPI  
drwxr-xr-x 2 mthomas use300 6 Oct 7 14:15 OpenACC  
drwxr-xr-x 2 mthomas use300 6 Oct 7 14:15 OPENMP  
[mthomas@login01 examples]$ ls -al MPI  
total 63  
drwxr-xr-x 2 mthomas use300 6 Oct 7 14:15 .  
drwxr-xr-x 6 mthomas use300 6 Oct 7 14:15 ..  
-rwxr-xr-x 1 mthomas use300 21576 Oct 7 14:15 hello_mpi  
-rw-r--r-- 1 mthomas use300 329 Oct 7 14:15 hello_mpi.f90  
-rw-r--r-- 1 mthomas use300 464 Oct 7 14:15 hellompi-slurm.sb  
-rw-r--r-- 1 mthomas use300 181 Oct 7 14:15 README.txt
```

Using Login Nodes Properly

- The login nodes are meant for file editing, simple data analysis, & tasks that use minimal compute resources.
- All computationally demanding jobs should be submitted and run through the batch queuing system.
- **Do not use the login nodes for:**
 - computationally intensive processes,
 - as hosts for running workflow management tools
 - as primary data transfer nodes for large or numerous data transfers
 - as servers providing other services accessible to the Internet.
 - running Jupyter notebooks
- **Login nodes are not the same as the batch nodes.**
 - Users should request an interactive sessions to compile ;arge programs.

Coming Soon: Expanse User Portal

- Quick and easy way for Expanse users to login, transfer and edit files and submit and monitor jobs.
- Gateway for launching interactive applications such as MATLAB, Rstudio
- Integrated web-based environment for file management and job submission.
- All Users with valid Expanse Allocation and XSEDE Based credentials have access via their XSEDE credentials..
- See: portal.comet.sdsc.edu



Outline

- Expanse Overview & Innovative Features
- Getting Started
- **Modules**
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

Expanse Environment Modules

- Expanse uses *Lmod*, a *Lua* based module system.
 - https://lmod.readthedocs.io/en/latest/010_user.html
- Users setup custom environments by loading available modules into the shell environment, *including needed compilers and libraries* and the batch scheduler.
- What's the same as Comet:
 - Dynamic modification of your shell environment
 - User can set, change, or delete environment variables
 - User chooses between different versions of the same software or different combinations of related codes.

Modules: What's Different?

- Users will need to load the scheduler (e.g. slurm)
- Users will *not* see all available modules when they run command "module available" *without loading a compiler*.
- Use the command "**module spider**" option to see if a particular package exists and can be loaded, run command

```
module spider <package>
```

```
module keywords <term>
```

- For additional details, and to identify module dependencies modules, use the command

```
module spider <application_name>
```

- The **module paths are different** for the CPU and GPU nodes. Users can enable the paths by loading the following modules:

```
module load cpu (for cpu nodes)
```

```
module load gpu (for gpu nodes)
```

- Avoid loading both modules

Module Command Examples

```
[mthomas@login01 ~]$ module list  
Currently Loaded Modules:  
1) shared 2) cpu/1.0 3) DefaultModules
```

{ List Current environment: list, li

```
[mthomas@login01 ~]$ module show DefaultModules
```

```
-----  
/usr/share/modulefiles/DefaultModules.lua:
```

```
load("shared")
```

```
load("cpu")
```

```
[mthomas@login01 ~]$ module available
```

```
----- /cm/shared/apps/spack/cpu/lmod/linux-centos8-x86_64/Core -----
```

```
aocc/2.2.0 emboss/6.6.0 gcc/9.2.0 intel/19.1.1.217
```

```
cmake/3.18.2 gcc/7.5.0 gcc/10.2.0 (D) ncurses/6.2
```

```
----- /cm/local/modulefiles -----
```

```
cluster-tools-dell/9.0 freeipmi/1.6.4 module-git shared (L)
```

```
cluster-tools/9.0 gcc/9.2.0 module-info singularitypro/3.5
```

```
cmd gpu/1.0 null slurm/expanse/20.02.3
```

```
[SNIP]
```

{ Show info about a module

{ Show available modules

Modules: Popular commands

Command	Description
module list	List the modules that are currently loaded
module avail	List the modules that are available in environment
module spider	List of the modules and extensions currently available
module display <module_name>	Show the environment variables used by <module name> and how they are affected
module unload <module name>	Remove <module name> from the environment
module load <module name>	Load <module name> into the environment
module swap <module one> <module two>	Replace <module one> with <module two> in the environment
module help	get a list of all the commands that module knows about do:
Shorthand notation: ml foo ml -bar	“ml” == module load foo “ml -bar” == module unload bar

SDSC Guidance: add module calls to your environment and batch scripts

Module Command Examples

Load a module, and verify that it has changed your environment

```
[mthomas@login01 ~]$ env
HOSTNAME=expanse-ln3.sdsc.edu
INTEL_LICENSE_FILE=/opt/intel/composer_xe_2013_sp1.2.144/licenses:/opt/intel/licenses:/root/intel/licenses
MPIHOME=/opt/mvapich2/intel/ib
FFTWHOME=/opt/fftw/3.3.4/intel/mvapich2_ib
SDSCHOME=/opt/sdsc
PYTHONPATH=/opt/sdsc/lib
LINCLUDE=/opt/intel/composer_xe_2013_sp1.2.144/mkl/include
INTELHOME=/opt/intel/composer_xe_2013_sp1.2.144
G_BROKEN_FILERAMES=1
BASH_FUNC_module()=() { eval `/usr/bin/modulecmd bash $*` }
_=~/bin/env
[mthomas@login01 ~]$ module load hdf5
[mthomas@login01 ~]$ env | grep -i hdf5
LD_LIBRARY_PATH=/cm/shared/apps/hdf5/1.10.1/lib
__LMod_Ref_Count_Path=/cm/shared/apps/hdf5/1.10.1/bin:1;/usr/local/bin:1;/usr/bin:1;/usr/local/sbin:1;/usr/sbin:1;/opt/dell/srvadmin/bin:1;/home/mthomas/.local/bin:1;/home/mthomas/bin:1
__LMod_Ref_Count__LMFILES_=/_cm/local/modulefiles/shared:1;/cm/local/modulefiles/cpu/1.0.lua:1;/usr/share/modulefiles/DefaultModules.lua:1;/cm/shared/modulefiles/hdf5/1.10.1:1
__LMod_Ref_Count_LD_Library_Path=/cm/shared/apps/hdf5/1.10.1/lib:1
__LMod_Ref_Count_LoadedModules=shared:1;cpu/1.0:1;DefaultModules:1;hdf5/1.10.1:1
LOADEDMODULES=shared:cpu/1.0:DefaultModules:hdf5/1.10.1
HDF5INCLUDE=/cm/shared/apps/hdf5/1.10.1/include
HDF5LIB=hdf5
HDF5DIR=/cm/shared/apps/hdf5/1.10.1/lib
PATH=/cm/shared/apps/hdf5/1.10.1/bin:/usr/local/bin:/usr/bin:/usr/local/sbin:/usr/sbin:/opt/dell/srvadmin/bin:/home/mthomas/.local/bin:/home/mthomas/bin
__LMFILES_=/_cm/local/modulefiles/shared:/cm/local/modulefiles/cpu/1.0.lua:/usr/share/modulefiles/DefaultModules.lua:/cm/shared/modulefiles/hdf5/1.10.1
[mthomas@login01 ~]
```

What happens if you log out?

Module: check Environment

Once you have loaded the modules, you can check the system variables that are available for you to use.

```
[mthomas@login01 ~]$ env | grep -i hdf5
[mthomas@login01 ~]$ module add hdf5
[mthomas@login01 ~]$ env | grep -i hdf5
LD_LIBRARY_PATH=/cm/shared/apps/hdf5/1.10.1/lib
__LMOD_REF_COUNT_PATH=/cm/shared/apps/hdf5/1.10.1/bin:1;/usr/local/bin:1;/usr/bin:1;/usr/local/sbin:1;/usr/sbin:1;/opt/dell/srvadmin/bin:1;/home/mthomas/.local/bin:1;/home/mthomas/bin:1
__LMOD_REF_COUNT_LMFILES_=cm/local/modulefiles/shared:1;/cm/local/modulefiles/cpu/1.0.lua:1;/usr/share/modulefiles/DefaultModules.lua:1;/cm/shared/modulefiles/hdf5/1.10.1:1
__LMOD_REF_COUNT_LD_LIBRARY_PATH=/cm/shared/apps/hdf5/1.10.1/lib:1
__LMOD_REF_COUNT_LOADEDMODULES=shared:1;cpu/1.0:1;DefaultModules:1;hdf5/1.10.1:1
LOADEDMODULES=shared:cpu/1.0:DefaultModules:hdf5/1.10.1
HDF5INCLUDE=/cm/shared/apps/hdf5/1.10.1/include
HDF5LIB=hdf5
HDF5DIR=/cm/shared/apps/hdf5/1.10.1/lib
PATH=/cm/shared/apps/hdf5/1.10.1/bin:/usr/local/bin:/usr/bin:/usr/local/sbin:/usr/sbin:/opt/dell/srvadmin/bin:/home/mthomas/.local/bin:/home/mthomas/bin
__LMFILES_=cm/local/modulefiles/shared:/cm/local/modulefiles/cpu/1.0.lua:/usr/share/modulefiles/DefaultModules.lua:/cm/shared/modulefiles/hdf5/1.10.1
```

What happens if you log out?

Loading Modules During Login

- Users can override and add to the standard set of login modules in two ways. The first is adding module commands to your personal startup files. The second way is through the “module save” command.
- For Bash:
 - Put the following block into your `~/.bash_profile` file

```
if [ -f ~/.bashrc ]; then
    . ~/.bashrc
fi
```

- Place the following in your `~/.bashrc` file:

```
if [ -z "$BASHRC_READ" ]; then
    export BASHRC_READ=1
    # Place any module commands here
    # module load hdf5
fi
```

Module: Login Environment

```
[mthomas@login02 ~]$ cat .bash_profile
# .bash_profile
# Get the aliases and functions
if [ -f ~/.bashrc ]; then
. ~/.bashrc
fi
[SNIP]
[mthomas@login01 ~]$
[mthomas@login02 ~]$ cat .bashrc
# .bashrc
# Source global definitions
if [ -f /etc/bashrc ]; then
. /etc/bashrc
fi
if [ -z "$BASHRC_READ" ]; then
export BASHRC_READ=1
# Place any module commands here
module load hdf5
F
[SNIP]
```

LOGOUT and LOG BACK IN:

(base) quantum:~ mthomas\$ expanse

Last login: Wed Oct 7 17:13:52 2020 from 76.176.117.51

[mthomas@login02 ~]\$ env | grep -i hdf5

```
LD_LIBRARY_PATH=/cm/shared/apps/hdf5/1.10.1/lib
__LMOD_REF_COUNT_PATH=/cm/shared/apps/hdf5/1.10.1/bin:1;/usr/local/bin:1;/usr/bin:1;/usr/local/sbin:1;/usr/sbin:1;/opt/dell/srvad
min/bin:1
__LMOD_REF_COUNT__LMFILES_=~/cm/local/modulefiles/shared:1;/cm/local/modulefiles/cpu/1.0.lua:1;/usr/share/modulefiles/DefaultModul
eModules.lua:1;/cm/shared/modulefiles/hdf5/1.10.1:1
```

Module: command not found

- Sometimes encountered when switching from one shell to another or attempting to run the module command from within a shell script or batch job.
- Module command may not be inherited to the shell
- To keep this from happening, execute the following command:
 - command line (interactive shells)
 - `source /etc/profile.d/modules.sh`
 - OR add to your shell script (including Slurm batch scripts)

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- **Account Management**
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

Multiple Allocations

- Many users will have access to multiple accounts and hence *projects*:
 - an allocation for a research project and a separate allocation for classroom or educational use
- Users should verify that the correct *project* is designated for all batch jobs.
- Awards are granted for a specific purposes and should not be used for other *projects*.
- To charge your job to one of your *projects*, replace << project >> with one from your list and put this PBS directive in your job script:
 - #SBATCH -A << project >>

Account Management

The `expanse-client` script provides additional details regarding User and Project availability and usage.

```
[user@expanse-login02 ~]$ /cm/shared/apps/sdsc/current/bin/expanse-client user -p  
NAME PROJECT USED AVAILABLE USED_BY_PROJECT
```

```
<user> <project> <SUs used by user> <SUs available for user> <SUs used by project>
```

Usage:

```
expanse-client [command]
```

Available Commands:

```
help Help about any command
```

```
project Get project information
```

```
user Get user information
```

Flags:

```
-h, --help help for expanse-client
```

```
-p, --plain plain no graphics output
```

```
-v, --verbose verbose output
```

Use "expanse-client [command] --help" for more information about a command.

Adding Users to an Account

- Project PIs and co-PIs can add or remove users from an account.
- To do this, log in to your XSEDE portal account and go to the Add User page

Charging

- Charge unit for all SDSC machines, including Expanse, is the Service Unit (SU). Corresponds to the use of:
 - CPU: one compute core, utilizing less than or equal to 1G of data for one hour
 - 1 GPU using less than 1G of data hour for 1 hour.
- Your charges are based on the resources that are tied up by your job, may not reflect how resources are used.
- Charges are based on either:
 - Number of cores
 - Fraction of the memory requested, whichever is larger.
- The minimum charge for any job is 1 SU.

Job Charge Considerations

- A node-exclusive job that runs on a compute node for one hour will be charged 128 SUs (128 cores x 1 hour)
- A node-exclusive job that runs on a GPU node for one hour will be charge 4GPU hours (4 GPU x 1 hour)
- A serial job in the shared queue that uses less than 1 GB memory and runs for one hour will be charged 1 SU (1 core x 1 hour)
- Each GPU node has 4 GPUs, ~384GB of memory and 128 cores
 - Default resource allocation for 1 GPU = 1 GPU, 1 CPU, and 1G of memory, users will need to explicitly ask for additional resources in their job script.
 - For max memory on a GPU node, users should request --mem = 374G
- A GPU SU is equivalent to 1GPU, >10CPUs, and >96G of memory.
- Multicore jobs will scale according to resource utilization
- Each standard compute node has ~256 GB of memory and 128 cores
 - Each standard node core will be allocated 1 GB of memory, users should explicitly include the --mem directive to request additional memory
 - Max. memory per compute node --mem = 248G
- Each large memory node has ~2 TB of memory and 128 cores
 - By default the system will only allocate 1 GB of memory per core, explicitly use the --mem directive to request additional memory
 - Max. memory per large memory node --mem = 2007G

Accounts

```
[mthomas@login02 ~]$ cat .bash_profile
# .bash_profile
# Get the aliases and functions
if [ -f ~/.bashrc ]; then
. ~/.bashrc
fi
[SNIP]
[mthomas@login01 ~]$
[mthomas@login02 ~]$ cat .bashrc
# .bashrc
# Source global definitions
if [ -f /etc/bashrc ]; then
. /etc/bashrc
fi
if [ -z "$BASHRC_READ" ]; then
export BASHRC_READ=1
# Place any module commands here
module load hdf5
F
[SNIP]
```

LOGOUT and LOG BACK IN:

(base) quantum:~ mthomas\$ expanse

Last login: Wed Oct 7 17:13:52 2020 from 76.176.117.51

[mthomas@login02 ~]\$ env | grep -i hdf5

```
LD_LIBRARY_PATH=/cm/shared/apps/hdf5/1.10.1/lib
__LMOD_REF_COUNT_PATH=/cm/shared/apps/hdf5/1.10.1/bin:1;/usr/local/bin:1;/usr/bin:1;/usr/local/sbin:1;/usr/sbin:1;/opt/dell/srvad
min/bin:1
__LMOD_REF_COUNT__LMFILES_=~/cm/local/modulefiles/shared:1;/cm/local/modulefiles/cpu/1.0.lua:1;/usr/share/modulefiles/Default
tModules.lua:1;/cm/shared/modulefiles/hdf5/1.10.1:1
```

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- **Compiling**
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

Supported Compilers on Expanse

- CPU nodes
 - GNU, Intel, AOCC (AMD) compilers
 - multiple MPI implementations (OpenMPI, MVAPICH2, and IntelMPI).
 - A majority of applications have been built using *gcc/10.2.0* which *features AMD Rome* specific optimization flags (-march=znver2).
 - Intel, and AOCC compilers all have flags to support Advanced Vector Extensions 2 (AVX2).
- GPU Compiling:
 - Expanse GPU nodes have GNU, Intel, and PGI compilers.
 - Note: Expanse login nodes are not the same as the GPU nodes → all GPU codes must be compiled by requesting an interactive session on the GPU nodes.

AMD AOCC Compilers: CPU Only

Language	Serial	MPI	OpenMP	MPI + OpenMP
Fortran	flang	mpif90	ifort -openmp	mpif90 -openmp
C	clang	mpiclang	icc -openmp	mpicc -openmp
C++	clang++	mpiclang	icpc -openmp	mpicxx -openm

The AMD Optimizing C/C++ Compiler (AOCC) is only available on CPU nodes. AMD compilers can be loaded using the module load command:

```
$ module load aocc
```

For more information on the AMD compilers:

```
$ [flang | clang ] -help
```

Using the AOCC Compilers

- If you have modified your environment, you can reload by executing the module purge & load commands at the Linux prompt, or placing the load command in your startup file (`~/.cshrc` or `~/.bashrc`)
- Note: The examples below are for the simple “helloompi” examples shown below

```
[mthomas@login02 ~]$ module list
Currently Loaded Modules:
 1) shared  2) cpu/1.0  3) DefaultModules  4) hdf5/1.10.1  5) intel/ 19.1.1.217
## need to change multiple modules
[mthomas@login02 ~]$ module purge
[mthomas@login02 ~]$ module list
No modules loaded
[mthomas@login02 ~]$ module load slurm
[mthomas@login02 ~]$ module load cpu
[mthomas@login02 ~]$ module load gcc
[mthomas@login02 ~]$ module load openmpi/4.0.4
[mthomas@login02 ~]$ module list
Currently Loaded Modules:
 1) slurm/expanse/20.02.3  2) cpu/1.0  3) gcc/10.2.0  4) openmpi/4.0.4
[mthomas@login02 MPI]$ module swap intel aocc
Due to MODULEPATH changes, the following have been reloaded:
 1) openmpi/4.0.4
[mthomas@login02 ~]$ module list
Currently Loaded Modules:
 1) slurm/expanse/20.02.3  2) cpu/1.0  3) aocc/2.2.0  4) openmpi/4.0.4
[mthomas@login02 ~]$
```

Intel Compilers: GPU and GPU

- Default/Suggested Compilers to used based on programming model and languages:

	Serial	MPI	OpenMP	MPI + OpenMP
Fortran	ifort	mpif90	ifort -openmp	mpif90 -openmp
C	icc	mpicc	icc -openmp	mpicc -openmp
C++	icpc	mpicxx	icpc -openmp	mpicxx -openmp

- In this tutorial, we include hands-on examples that cover many of the cases in the table:
 - (1) MPI
 - (2) OpenMP
 - (3) HYBRID

Using the Intel Compilers

- If you have modified your environment, you can reload by executing the module purge & load commands at the Linux prompt, or placing the load command in your startup file (~/.cshrc or ~/.bashrc)

```
[mthomas@login02 ~]$ module list
[mthomas@login02 MPI]$ module list
Currently Loaded Modules:
 1) slurm/expanse/20.02.3  2) cpu/1.0  3) aocc/2.2.0  4) openmpi/4.0.4
[mthomas@login02 ~]$ module purge
[mthomas@login02 ~]$ module list
No modules loaded
[mthomas@login02 ~]$ module load slurm
[mthomas@login02 ~]$ module load cpu
[mthomas@login02 ~]$ module load intel
[mthomas@login02 ~]$ module load openmpi/4.0.4
[mthomas@login02 ~]$ module list
Currently Loaded Modules:
 1) slurm/expanse/20.02.3  2) cpu/1.0  3) aocc/2.2.0  4) openmpi/4.0.4
[mthomas@login02 ~]$
```

Using the Intel Compilers

- For Intel Advanced Vector Extensions (AVX2) support, compile with the `-xHOST` option.
 - https://en.wikipedia.org/wiki/Advanced_Vector_Extensions (128/256bit SIMD, Vector ops (MPI broadcast, gather, ...))
 - Note that `-xHOST` alone does not enable aggressive optimization, so compilation with `-O3` is also suggested.
 - The `-fast` flag invokes `-xHOST`, but should be avoided since it also turns on interprocedural optimization (`-ipo`), which may cause problems in some instances.
- Intel Math Kernel Lib (MKL) libraries are available as part of the "intel" modules on Expanse.
 - Once this module is loaded, the environment variable `INTEL_MKLHOME` points to the location of the mkl libraries and
 - Use MKL Link Advisor to see what libraries are recommended for your compiler and system configuration:
 - <https://software.intel.com/content/www/us/en/develop/articles/intel-mkl-link-line-advisor.html>

GNU Compilers: CPU and GPU

- The GNU compilers can be loaded by executing the following commands at the Linux prompt or placing in your startup files (~/.cshrc or ~/.bashrc)

```
[mthomas@login01 MPI]$ module purge
[mthomas@login01 MPI]$ module load slurm
[mthomas@login01 MPI]$ module load cpu
[mthomas@login01 MPI]$ module load gcc/10.2.0
[mthomas@login01 MPI]$ module load openmpi/4.0.4
[mthomas@login01 MPI]$ module list
Currently Loaded Modules:

 1) slurm/expanse/20.02.3  2) cpu/1.0  3) gcc/10.2.0  4) openmpi/4.0.4
```

- For AVX support, compile with -mavx.
- Note that AVX support is only available in version 4.7 or later, so it is necessary to explicitly load the gnu/4.9.2 module until such time that it becomes the default.
- For more information on the GNU compilers: man [gfortran | gcc | g++]

Using the GNU Compilers

Table of recommended GNU compilers:

	Serial	MPI	OpenMP	MPI+OpenMP
Fortran	gfortran	mpif90	gfortran -fopenmp	mpif90 -fopenmp
C	gcc	mpicc	gcc -fopenmp	mpicc -fopenmp
C++	g++	mpicxx	g++ -fopenmp	mpicxx -fopenmp

PGI Compilers: GPU Only

- PGI (formerly The Portland Group, Inc.), was a company that produced a set of commercially available Fortran, C and C++ compilers for high-performance computing systems.
- It is now owned by NVIDIA.
- To compile code, you need to obtain an interactive node.
- For AVX support, compile with -fast

```
#Environment
module purge
module load slurm
module load gpu
module load pgi
```

```
[$USER@expanse-ln2:~/expanse101/MKL] which mpicc
/opt/mvapich2/pgi(ib/bin/mpicc
```

- For more information on the PGI compilers run: man [pgf90 | pgcc | pgCC]

Recommended PGI Compilers

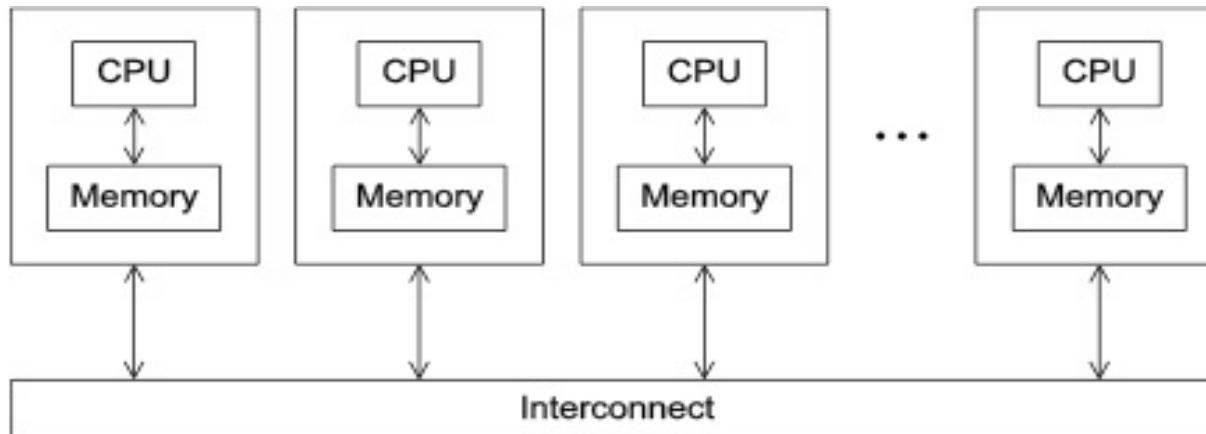
	Serial	MPI	OpenMP	MPI+OpenMP
Fortran	pgf90	mpif90	pgf90 -mp	mpif90 -mp
C	pgcc	mpicc	pgcc -mp	mpicc -mp
C++	pgCC	mpicxx	pgCC -mp	mpicxx -mp

- PGI supports the following high-level languages:
 - Fortran 77, 90/95/2003, 2008 (partial)
 - High Performance Fortran (HPF)
 - ANSI C99 with K&R extensions
 - ANSI/ISO C++
 - CUDA Fortran
 - OpenCL
 - OpenACC
 - OpenMP

Outline

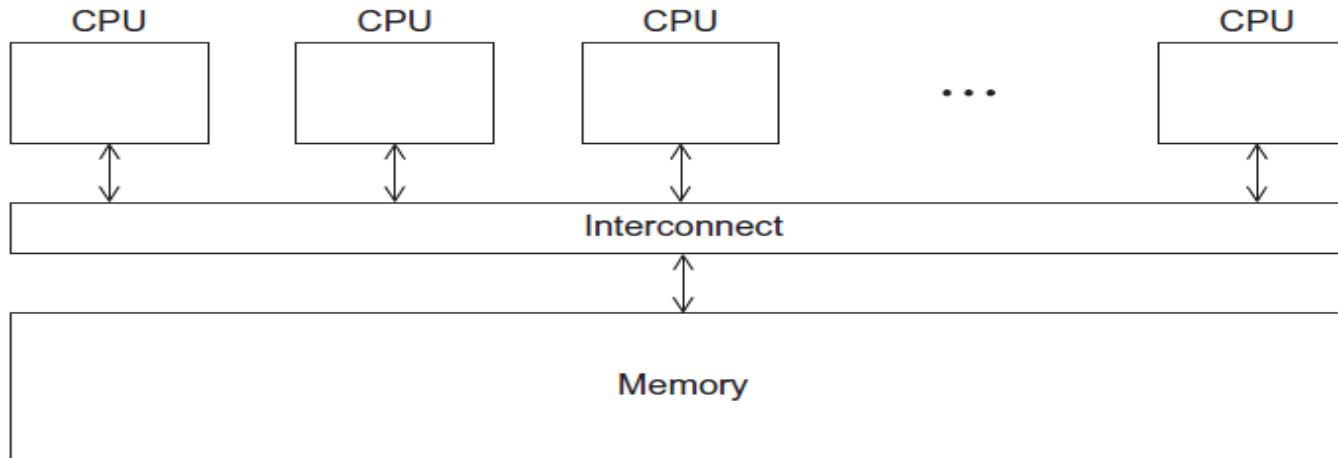
- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- **Running Jobs**
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

Parallel Models: Distributed Memory



- Programs that run asynchronously, pass messages for communication and coordination between resources.
- Examples include: SOA-based systems, massively multiplayer online games, peer-to-peer apps.
- Different types of implementations for the message passing mechanism: HTTP, RPC-like connectors, message queues
- HPC historically uses the **Message Passing Interface (MPI)**

Parallel Models: Shared Memory



- CPUs all share same localized memory (SHMEM);
 - Coordination and communication between tasks via interprocessor communication (IPC) or virtual memory mappings.
- May use: uniform or non-uniform memory access (UMA or NUMA); cache-only memory architecture (COMA).
- Most common HPC API's for using SHMEM:
 - Portable Operating System Interface (POSIX); Open Multi-Processing (OpenMP) designed for parallel computing – best for multi-core computing.

Running Jobs on Expanse

- When you run in the batch mode, you submit jobs to be run on the compute nodes using the sbatch command as described below.
- *Remember that computationally intensive jobs should be run only on the compute nodes and not the login nodes.*
- Expanse places limits on the number of jobs queued and running on a per group (allocation) and partition basis.
- Please note that submitting a large number of jobs (especially very short ones) can impact the overall scheduler response for all users.

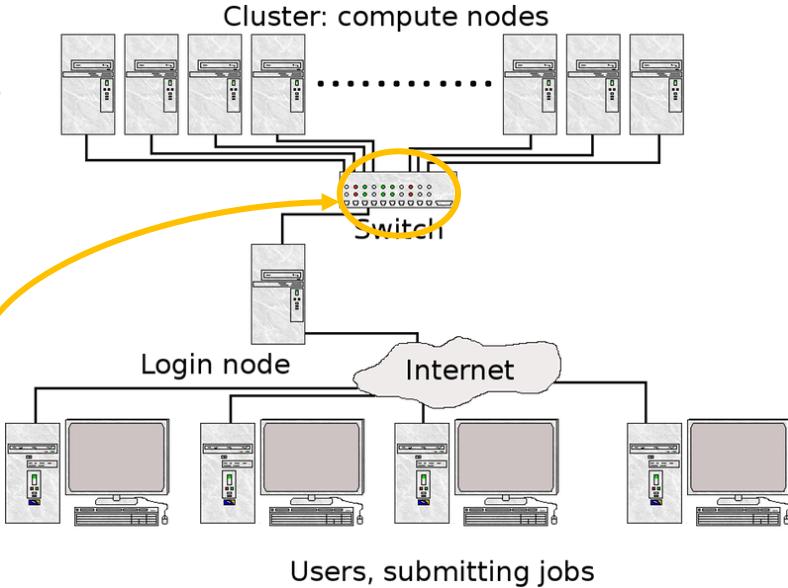
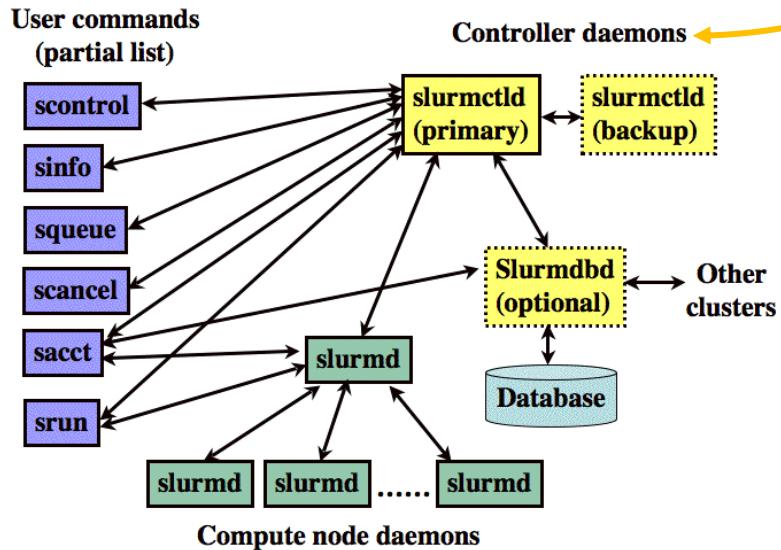
Methods for Running Jobs on Expanse

- Expanse uses the **Simple Linux Utility for Resource Management (SLURM)** batch environment.
 - **Batch Jobs:** Submit batch scripts to Slurm from the login nodes:
 - Partition (queue)
 - Time limit for the run (maximum of 48 hours)
 - Number of nodes, tasks per node; Memory requirements (if any)
 - Job name, output file location; Email info, configuration
- **Interactive Jobs:** Use the *srun* command to obtain nodes for ‘live,’ command line interactive access:
 - **CPU:**
`srun --partition=debug --qos=debug-normal --pty --nodes=1 --ntasks-per-node=128 --mem=248 -t 00:30:00 --wait=0 --export=ALL /bin/bash`
 - **GPU:**
`srun --pty --nodes=1 --ntasks-per-node=1 --cpus-per-task=10 -p gpu-debug --gpus=1 -t 00:10:00 /bin/bash`

Slurm Resource Manager

Simple Linux Utility for Resource Management

- “Glue” for parallel computer to schedule and execute jobs
- Role: Allocate resources within a cluster
 - Nodes (unique IP address)
 - Interconnect/switches
 - Generic resources (e.g. GPUs)
 - Launch and otherwise manage jobs



- **Functionality:**
 - Prioritize queue(s) of jobs;
 - decide when and where to start jobs;
 - terminate job when done;
 - Appropriate resources;
 - manage accounts for jobs

Slurm Partitions on Expanse

Partition limits subject to change based on Early User Period evaluation

Partition Name	QOS	Max Walltime	Max Nodes/Job	Max RunningJobs	Max Running + Queued Jobs	Charge Factor	Comments
compute	normal	48 hrs	32	64	128	1	Used for exclusive access to regular compute nodes
shared	shared-normal	48 hrs	1	4096	4096	1	Single-node jobs using fewer than 128 cores
gpu	gpu-normal	48 hrs	4	16	24	1	Used for exclusive access to the GPU nodes
gpu-shared	gpu-shared-normal	48 hrs	1	16	24	1	Single-node job using fewer than 4 GPUs
large-shared	large-shared-normal	48 hrs	1	1	4	1	Single-node jobs using large memory up to 2 TB (minimum memory required 256G)
debug	debug-normal	15 min	2	1	2	1	Priority access to compute nodes set aside for testing of jobs with short walltime and limited resources
gpu-debug	gpu-debug-normal	15 min	2	1	2	1	** Priority access to gpu nodes set aside for testing of jobs with short walltime and limited resources
preempt	preempt-normal	7 days	32		128	.8	Discounted jobs to run on free nodes that can be pre-empted by jobs submitted to any other queue (NO REFUNDS)
preempt-gpu	preempt-gpu-normal	7 days	1			.8	Discounted jobs to run on unallocated nodes that can be pre-empted by jobs submitted to higher priority queues (NO REFUNDS)

Common Slurm Commands

- Submit jobs using the `sbatch` command:

```
$ sbatch mycode-slurm.sb
```

Submitted batch job 8718049

- Check job status using the `squeue` command:

```
$ squeue -u $USER
```

JOBID	PARTITION	NAME	USER	ST	TIME	NODES	NODELIST(REASON)
8718049	compute	mycode	user	PD	0:00	1	(Priority)

- Once the job is running:

```
$ squeue -u $USER
```

JOBID	PARTITION	NAME	USER	ST	TIME	NODES	NODELIST(REASON)
8718049	debug	mycode	user	R	0:02	1	expanse-14-01

- Cancel a running job:

```
$ scancel 8718049
```

Example Batch Script

```
[mthomas@login01 ENV_INFO]$ cat env-slurm.sb
#!/bin/bash
#SBATCH --job-name="envinfo"
#SBATCH --output="envinfo.%j.%N.out"
#SBATCH --partition=compute
#SBATCH --nodes=1
#SBATCH --ntasks-per-node=1
#SBATCH --export=ALL
#SBATCH -t 00:01:00

## Environment
module purge
module load slurm
module load cpu

## perform some basic unix commands
echo "-----"
echo "hostname= `hostname`"
echo "date= `date`"
echo "whoami= `whoami`"
echo "pwd= `pwd`"
echo "module list= `module list`"
echo "-----"
echo "env= `env`"
echo "-----"
```

Simple batch script showing environment, date, etc.

```
[mthomas@login01 ENV_INFO]$ cat envinfo.108867.exp-6-56.out
-----
hostname= exp-6-56
date= Wed Oct 7 23:45:43 PDT 2020
whoami= mthomas
pwd= /home/mthomas/DEMO/ENV_INFO
Currently Loaded Modules:
 1) slurm/expanse/20.02.3 2) cpu/1.0
-----
env= SLURM_MEM_PER_CPU=1024
LD_LIBRARY_PATH=/cm/shared/apps/slurm/current/lib64/slurm:/cm/shared/apps/slurm/current/lib64 LS_COLORS=rs=0

[SNIP]

MODULESHOME=/usr/share/lmod/lmod LMOD_SETTARG_FULL_SUPPORT=no
HISTSIZE=5000 LMOD_PKG=/usr/share/lmod/lmod
LMOD_CMD=/usr/share/lmod/lmod/libexec/lmod SLURM_LOCALID=0
LESSOPEN=||/usr/bin/lesspipe.sh %s LMOD_FULL_SETTARG_SUPPORT=no
LMOD_DIR=/usr/share/lmod/lmod/libexec BASH_FUNC_module%%=() { eval
$(${LMOD_CMD} bash "$@") && eval ${${LMOD_SETTARG_CMD}::-} -s sh }
BASH_FUNC_ml%%=() { eval ${${LMOD_DIR}/ml_cmd "$@") }_=/usr/bin/env
-----
```

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- **Hands-on Examples**
 - GPU/CUDA Jobs
 - OpenMP Jobs
 - MPI Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

Hands On Examples

- GPU
- CPU:
 - OpenMP
 - MPI
 - HYBRID
- Large Memory Nodes

General Steps: Compiling/Running Jobs

- Change to a working directory (for example the `expanse101` directory):

```
cd /home/$USER/expanse101/MPI
```

- Verify that the correct modules loaded:

```
module list
```

Currently Loaded Modulefiles:

1) slurm/expanse/20.02.3 2) cpu/1.0 3) gcc/10.2.0 4) openmpi/4.0.4

- Compile the MPI hello world code:

```
mpif90 -o hello_mpi hello_mpi.f90
```

- Verify executable has been created (check that date):

```
ls -lt hello_mpi
```

-rwxr-xr-x 1 user sdsc 721912 Mar 25 14:53 **hello_mpi**

- Submit job

```
sbatch hello_mpi_slurm.sb
```

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - **MPI Jobs**
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

MPI Hello World

- Change to the MPI examples directory:

```
[mthomas@login01 MPI]$ cat hello_mpi.f90
! Fortran example
program hello
include 'mpif.h'
integer rank, size, ierror, tag, status(MPI_STATUS_SIZE)

call MPI_INIT(ierror)
call MPI_COMM_SIZE(MPI_COMM_WORLD, size, ierror)
call MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierror)
print*, 'node', rank, ': Hello world!'
call MPI_FINALIZE(ierror)
end
[mthomas@login01 MPI]$
```

MPI Hello World: Compile

Set the environment and then compile the code

```
[mthomas@login01 MPI]$ cat README.txt
[1] Compile:

# Load module environment
module purge
module load slurm
module load cpu
module load gcc/10.2.0
module load openmpi/4.0.4

mpif90 -o hello_mpi hello_mpi.f90
```

[2a] Run using Slurm:

```
sbatch hellompi-slurm.sb
```

[2b] Run using Interactive CPU Node

```
srun --partition=debug --pty --account=use300 --nodes=1 --ntasks-per-node=128 --mem=248G -t
00:30:00 --wait=0 --export=ALL /bin/bash
```

```
[mthomas@login01 MPI]$ module list
```

Currently Loaded Modules:

1) cpu/1.0 2) slurm/expanse/20.02.3

```
[mthomas@login01 MPI]$ module purge
```

```
[mthomas@login01 MPI]$ module load slurm
```

```
[mthomas@login01 MPI]$ module load cpu
```

```
[mthomas@login01 MPI]$ module load gcc/10.2.0
```

```
[mthomas@login01 MPI]$ module load openmpi/4.0.4
```

```
[mthomas@login01 MPI]$ module list
```

Currently Loaded Modules:

1) slurm/expanse/20.02.3 2) cpu/1.0 3) gcc/10.2.0 4) openmpi/4.0.4

```
[mthomas@login01 MPI]$ mpif90 -o hello_mpi hello_mpi.f90
```

```
[mthomas@login01 MPI]$
```

MPI Hello World: Batch Script

- To run the job, use the **batch script submission** command.
- Monitor the job until it is finished using the **squeue** command.

```
[mthomas@login01 MPI]$ cat hellompi-slurm-gnu.sb
#!/bin/bash
#SBATCH --job-name="hellompi-gnu"
#SBATCH --output="hellompi-gnu.%j.%N.out"
#SBATCH --partition=compute
#SBATCH --nodes=2
#SBATCH --ntasks-per-node=128
#SBATCH --export=ALL
#SBATCH -t 00:10:00

#This job runs with 2 nodes,
128 cores per node for a total of 256 cores.

## Environment
module purge
module load slurm
module load cpu
module load gcc/10.2.0
module load openmpi/4.0.4

## Use srun to run the job

srun --mpi=pmi2 -n 256 --cpu-bind=rank ./hello_mpi_gnu

[mthomas@login01 MPI]$
```

```
[mthomas@login01 MPI]$ sbatch hellompi-slurm-gnu.sb; squeue -u mthomas
Submitted batch job 108910
      JOBID PARTITION  NAME   USER ST   TIME NODES NODELIST(REASON)
      108910  compute  hellompi  mthomas PD   0:00    2 (None)
[mthomas@login01 MPI]$ cat hellompi-gnu.108910.exp-12-54.out
node    4 : Hello world!
node    5 : Hello world!
node    7 : Hello world!
node    0 : Hello world!
node    2 : Hello world!
node    3 : Hello world!
node    9 : Hello world!
node   10 : Hello world!

[SNIP]

node  247 : Hello world!
node  248 : Hello world!
node  249 : Hello world!
node  186 : Hello world!
node  220 : Hello world!
node  203 : Hello world!
node  135 : Hello world!
```

Using An Interactive mode

```
[mthomas@login01 MPI]$ module purge
[mthomas@login01 MPI]$ module load slurm
[mthomas@login01 MPI]$ module load cpu
[mthomas@login01 MPI]$ module load gcc/10.2.0
[mthomas@login01 MPI]$ module load openmpi/4.0.4
[mthomas@login01 MPI]$ srun --pty --nodes=1 --ntasks-per-node=24 -p debug -t 00:30:00 --wait 0 /bin/bash
[mthomas@exp-9-55 MPI]$ module list
```

Request
interactive
node for 30
minutes

```
[mthomas@exp-9-55 MPI]$ mpirun -np 16 ./hello_mpi
node 1 : Hello world!
node 15 : Hello world!
node 7 : Hello world!
node 14 : Hello world!
node 11 : Hello world!
node 6 : Hello world!
node 4 : Hello world!
node 5 : Hello world!
node 12 : Hello world!
node 13 : Hello world!
node 0 : Hello world!
node 8 : Hello world!
node 9 : Hello world!
node 10 : Hello world!
node 2 : Hello world!
node 3 : Hello world!
```

- Exit interactive session when your work is done or you will be charged CPU time.
- Beware of oversubscribing your job: asking for more cores than you have. Intel compiler allows this, but your performance will be degraded.

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - **OpenMP Jobs**
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

OpenMP Hello World

Change to the OPENMP examples directory:

```
[mthomas@login01 examples]$ cd OPENMP/
[mthomas@login01 OPENMP]$ ll
total 89
drwxr-xr-x 2 mthomas use300 7 Oct 7 11:28 .
drwxr-xr-x 7 mthomas use300 7 Oct 8 00:03 ..
-rw xr-xr-x 1 mthomas use300 19640 Oct 7 11:28 hello_openmp
-rw r--r-- 1 mthomas use300 236 Oct 7 11:28 hello_openmp.f90
-rw r--r-- 1 mthomas use300 672 Oct 7 11:28 hello_openmp_shared.108737.exp-6-56.out
-rw r--r-- 1 mthomas use300 442 Oct 7 11:28 openmp-slurm-shared.sb
-rw r--r-- 1 mthomas use300 168 Oct 7 11:28 README.txt
[mthomas@login01 OPENMP]$ cat hello_openmp.f90
  PROGRAM OMPHELLO
  INTEGER TNUMBER
  INTEGER OMP_GET_THREAD_NUM

!$OMP PARALLEL DEFAULT(PRIVATE)
  TNUMBER = OMP_GET_THREAD_NUM()
  PRINT *, 'HELLO FROM THREAD NUMBER = ', TNUMBER
!$OMP END PARALLEL

END
```

OpenMP Hello World: Compile (using aocc compiler)

Set the environment and
then compile the code

```
[mthomas@login01 OPENMP]$ cat README.txt  
[1] Compile:
```

```
#load module environmentmodule  
module purge  
module load slurm  
module load cpu  
module load aocc
```

```
flang -fopenmp -o hello_openmp hello_openmp.f90
```

```
[2] Run:
```

```
sbatch openmp-slurm-shared.sb
```

```
[mthomas@login01 OPENMP]$
```

```
[mthomas@login01 OPENMP]$ module list  
  
[mthomas@login01 OPENMP]$ module purge  
[mthomas@login01 OPENMP]$ module load slurm  
[mthomas@login01 OPENMP]$ module load cpu  
[mthomas@login01 OPENMP]$ module load aocc
```

Currently Loaded Modules:
1) slurm/expanse/20.02.3 2) cpu/1.0 3) aocc/2.2.0

```
[mthomas@login01 OPENMP]$
```

```
[mthomas@login01 MPI]$ mpif90 -o hello_mpi hello_mpi.f90
```

OpenMP Hello World: Controlling #Threads

A key issue when running OpenMP code is controlling thread behavior.

If you run from command line, it will work, but it is not recommended because you will be using Pthreads, which automatically picks the number of threads - in this case 24.

```
[expanse-ln2:~/expanse1010/PENMP] ./hello_openmp
Hello from Thread Number[      0 ] and Welcome Webinar!
Hello from Thread Number[      2 ] and Welcome Webinar!
.
.
.
Hello from Thread Number[    22 ] and Welcome Webinar!
Hello from Thread Number[    11 ] and Welcome Webinar!
Hello from Thread Number[    23 ] and Welcome Webinar!
```

To control thread behavior, there are several key environment variables:

OMP_NUM_THREADS controls the number of threads allowed, and OMP_PROC_BIND binds threads to “places” (e.g. cores) and keeps them from moving around (between cores).

```
[expanse-ln2:~/expanse1010PE/NMP] export OMP_NUM_THREADS=4; ./hello_openmp
HELLO FROM THREAD NUMBER = 3
HELLO FROM THREAD NUMBER = 1
HELLO FROM THREAD NUMBER = 2
HELLO FROM THREAD NUMBER = 0
```

See: https://www.ibm.com/support/knowledgecenter/SSGH2K_13.1.3/com.ibm.xlc1313.aix.doc/compiler_ref/ruomprun.html

OpenMP Hello World: Batch Script

```
[mthomas@login01 OPENMP]$ cat openmp-slurm-shared.sb
#!/bin/bash
#SBATCH --job-name="hell_openmp_shared"
#SBATCH --output="hello_openmp_shared.%j.%N.out"
#SBATCH --partition=shared
#SBATCH --nodes=1
#SBATCH --ntasks-per-node=1
#SBATCH --cpus-per-task=16
#SBATCH --mem=32G
#SBATCH --export=ALL
#SBATCH -t 01:30:00

# AOCC environment
module purge
module load slurm
module load cpu
module load aocc

#SET the number of openmp threads
export OMP_NUM_THREADS=16

#Run the openmp job
./hello_openmp
[mthomas@login01 OPENMP]$
```

```
[expanse-ln2:~/expanse101/OPENMP] cat openmp-slurm-shared.sb
#!/bin/bash
#SBATCH --job-name="hell_openmp_shared"
#SBATCH --output="hello_openmp_shared.%j.%N.out"
#SBATCH --partition=shared
#SBATCH --share
#SBATCH --nodes=1
#SBATCH --ntasks-per-node=16
#SBATCH --mem=80G
#SBATCH --export=ALL
#SBATCH -t 01:30:00

#SET the number of openmp threads
export OMP_NUM_THREADS=16

#Run the openmp job
./hello_openmp
```

- Note: Expanse supports **shared-node jobs** (more than one job on a single node).
- Many applications are serial or can only scale to a few cores.
- Shared nodes improve job throughput, provide higher overall system utilization, and allow more users to run on nodes.

OpenMP Hello World: submit job & monitor

To run the job, type the **batch script submission** command:

```
[mthomas@login01 OPENMP]$ sbatch openmp-slurm-shared.sb ; squeue -u mthomas
Submitted batch job 108911
      JOBID PARTITION  NAME   USER ST    TIME NODES NODELIST(REASON)
 108911  shared hell_ope mthomas PD    0:00     1 (None)
[mthomas@login01 OPENMP]$ ll
total 98
drwxr-xr-x 2 mthomas use300 8 Oct  8 03:37 .
drwxr-xr-x 7 mthomas use300 7 Oct  8 00:03 ..
-rwxr-xr-x 1 mthomas use300 19640 Oct  7 11:28 hello_openmp
-rw-r--r-- 1 mthomas use300 236 Oct  7 11:28 hello_openmp.f90
-rw-r--r-- 1 mthomas use300 672 Oct  8 03:37 hello_openmp_shared.108911.exp-6-56.out
-rw-r--r-- 1 mthomas use300 442 Oct  7 11:28 openmp-slurm-shared.sb
-rw-r--r-- 1 mthomas use300 168 Oct  7 11:28 README.txt
```

```
[mthomas@login01 OPENMP]$ cat
hello_openmp_shared.108911.exp-6-56.out
HELLO FROM THREAD NUMBER = 7
HELLO FROM THREAD NUMBER = 6
HELLO FROM THREAD NUMBER = 12
HELLO FROM THREAD NUMBER = 10
HELLO FROM THREAD NUMBER = 1
HELLO FROM THREAD NUMBER = 2
HELLO FROM THREAD NUMBER = 5
HELLO FROM THREAD NUMBER = 0
HELLO FROM THREAD NUMBER = 4
HELLO FROM THREAD NUMBER = 3
HELLO FROM THREAD NUMBER = 13
HELLO FROM THREAD NUMBER = 15
HELLO FROM THREAD NUMBER = 14
HELLO FROM THREAD NUMBER = 11
HELLO FROM THREAD NUMBER = 9
HELLO FROM THREAD NUMBER = 8
[mthomas@login01 OPENMP]$
```

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - **GPU/CUDA Jobs**
 - Hybrid MPI-OpenMP Jobs
- Data and Storage
- Final Comments

Expanse GPU Hardware

GPU Nodes	
GPU Type	NVIDIA V100 SMX2
Nodes	52
GPUs/node	4
CPU Type	Xeon Gold 6248
Cores/socket	20
Sockets	2
Clock speed	2.5 GHz
Flop speed	34.4 TFlop/s
Memory capacity	*384 GB DDR4 DRAM
Local Storage	1.6TB Samsung PM1745b NVMe PCIe SSD
Max CPU Memory bandwidth	281.6 GB/s

Using GPU Nodes

- GPU nodes are allocated as a separate resource. The conversion rate is (TBD) Expanse Service Units (SUs) to 1 V100 GPU-hour.
- Login nodes are not the same as the GPU nodes:
 - → GPU codes must be compiled by requesting an interactive session on a GPU nodes.
- Batch: GPU nodes can be accessed via either the "gpu" or the "gpu-shared" partitions.
 - #SBATCH -p gpu
 - or #SBATCH -p gpu-shared
- Interactive GPU node:
 - `srun --pty --nodes=1 --ntasks-per-node=1 --cpus-per-task=10 -p gpu-debug --gpus=1 -t 00:10:00 /bin/bash`

GPU/CUDA: Interactive Node

- Change to the OpenACC directory

```
[mthomas@exp-7-59 OpenACC]$ ll
total 71
-rw-r--r-- 1 mthomas use300 2136 Oct  7 11:28 laplace2d.c
-rwxr-xr-x 1 mthomas use300 52056 Oct  7 11:28 laplace2d.openacc.exe
-rw-r--r-- 1 mthomas use300  234 Oct  7 11:28 OpenACC.108739.exp-7-57.out
-rw-r--r-- 1 mthomas use300  307 Oct  8 00:21 openacc-gpu-shared.sb
-rw-r--r-- 1 mthomas use300 1634 Oct  7 11:28 README.txt
-rw-r--r-- 1 mthomas use300 1572 Oct  7 11:28 timer.h
```

- Obtain an interactive node:

```
[mthomas@login01 OpenACC]$ srun --pty --nodes=1 --ntasks-per-node=1 --cpus-per-
task=10 -p gpu-debug --gpus=1 -t 00:10:00 /bin/bash
```

GPU/CUDA: Node Information

Check node configuration:

```
[mthomas@exp-7-59 OpenACC]$ nvidia-smi
Thu Oct 8 03:58:44 2020
+
| NVIDIA-SMI 450.51.05 Driver Version: 450.51.05 CUDA Version: 11.0 |
+-----+
| 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 32C P0 41W / 300W | 0MiB / 32510MiB | 0% Default |
| | | N/A |
+-----+
+
| Processes:                               |
| GPU  GI  CI  PID Type Process name      GPU Memory |
| ID  ID          Usage   |
+-----+
| No running processes found               |
+-----+
[mthomas@exp-7-59 OpenACC]$
```

GPU: Compile on Interactive node

```
[mthomas@login01 OpenACC]$  
cat README.txt  
[1] Compile Code:  
(a) Get an interactive GPU debug node:  
module load slurm  
srun --pty --nodes=1 --ntasks-per-node=1 --cpus-per-task=10 -p gpu-debug --gpus=1 -t 00:10:00 /bin/bash  
  
(b) On the GPU node:  
module purge  
module load slurm  
module load gpu  
module load pgf  
pgcc -o laplace2d.openacc.exe -fast -Minfo -acc -ta=tesla:cc70 laplace2d.c  
  
Compiler output:  
GetTimer:  
 20, include "timer.h"  
 61, FMA (fused multiply-add) instruction(s) generated  
laplace:  
 47, Loop not fused: function call before adjacent loop  
    Loop unrolled 8 times  
    FMA (fused multiply-add) instruction(s) generated  
 55, StartTimer inlined, size=2 (inline) file laplace2d.c (37)  
  
[SNIP]  
 75, #pragma acc loop gang, vector(4) /* blockIdx.y threadIdx.y */  
 77, #pragma acc loop gang, vector(32) /* blockIdx.x threadIdx.x */  
 88, GetTimer inlined, size=9 (inline) file laplace2d.c (54)  
(Exit out of debug node after this)  
  
[2] Run job:  
sbatch openacc-gpu-shared.sb
```

GPU: Submit Batch Script on CPU node

```
[mthomas@login01 OpenACC]$ cat openacc-gpu-shared.sb
#!/bin/bash
#SBATCH --job-name="OpenACC"
#SBATCH --output="OpenACC.%j.%N.out"
#SBATCH --partition=gpu-shared
#SBATCH --nodes=1
#SBATCH --ntasks-per-node=1
#SBATCH --gpus=1
#SBATCH -t 01:00:00

#Environment
module purge
module load slurm
module load gpu
module load pgi

#Run the job
./laplace2d.openacc.exe
```

```
[mthomas@login01 OpenACC]$ sbatch openacc-gpu-shared.sb
[mthomas@login01 OpenACC]$ sbatch openacc-gpu-shared.sb ; squeue -u mthomas
Submitted batch job 108915
      JOBID PARTITION  NAME   USER ST      TIME  NODES NODELIST(REASON)
    108915  gpu-share  OpenACC  mthomas  PD      0:00    1 (None)
```

```
[mthomas@login01 OpenACC]$ cat OpenACC.108915.exp-7-57.out
main()
Jacobi relaxation Calculation: 4096 x 4096 mesh
 0, 0.250000
100, 0.002397
200, 0.001204
300, 0.000804
400, 0.000603
500, 0.000483
600, 0.000403
700, 0.000345
800, 0.000302
900, 0.000269
total: 1.084470 s
[mthomas@login01 OpenACC]$
```

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - **Hybrid MPI-OpenMP Jobs**
- Data and Storage
- Final Comments

Hybrid MPI + OpenMP Hello World

```
#include <stdio.h>
#include "mpi.h"
#include <omp.h>

int main(int argc, char *argv[]) {
    int numprocs, rank, namelen;
    char processor_name[MPI_MAX_PROCESSOR_NAME];
    int iam = 0, np = 1;

    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
    MPI_Get_processor_name(processor_name, &namelen);

    #pragma omp parallel default(shared) private(iam, np)
    {
        np = omp_get_num_threads();
        iam = omp_get_thread_num();
        printf("Hello Webinar participants from thread %d out of %d from process %d out of
%d on %s\n",
               iam, np, rank, numprocs, processor_name);
    }

    MPI_Finalize();
}
```

Hybrid MPI + OpenMP Jobs

```
[mthomas@login01 HYBRID]$ cat README.txt
```

[1] Compile:

```
# Load module environment
module purge
module load slurm
module load cpu
module load intel
module load intel-mpi

export I_MPI_CC=icc
mpicc -fopenmp -o hello_hybrid hello_hybrid.c
```

[2] Run:

```
sbatch hybrid-slurm.sb
```

```
[mthomas@login01 HYBRID]$ cat hybrid-slurm.sb
#!/bin/bash
#SBATCH --job-name="hellohybrid"
#SBATCH --output="hellohybrid.%j.%N.out"
#SBATCH --partition=shared
#SBATCH --nodes=1
#SBATCH --ntasks-per-node=2
#SBATCH --cpus-per-task=16
#SBATCH -B 2:16:1
#SBATCH --export=ALL
#SBATCH -t 01:30:00

# Load Module Environment
module purge
module load slurm
module load cpu
module load intel
module load intel-mpi

#Run
export OMP_NUM_THREADS=16
mpirun -genv I_MPI_PIN_DOMAIN=omp:compact ./hello_hybrid
```

```
[mthomas@login01 HYBRID]$ mpicc -fopenmp -o hello_hybrid hello_hybrid.c
```

```
[mthomas@login01 HYBRID]$ sbatch hybrid-slurm.sb
```

```
Submitted batch job 108875
```

```
[mthomas@login01 HYBRID]$ squeue -u mthomas
```

JOBID	PARTITION	NAME	USER	ST	TIME	NODES	NODELIST(REASON)
108875	shared	hellohyb	mthomas	PD	0:00	1	(None)

```
[mthomas@login01 HYBRID]$
```

Hybrid Hello World: Output

Code ran on:

- 1 node,
- 2 cores per node,
- 16 threads per core

```
[expanse-ln2:~/expanse101/HYBRID] cat hellohybrid.108875.expanse-06-48.out | sort
Hello from thread 0 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 0 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 1 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 1 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 2 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 2 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 3 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 3 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 4 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 4 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 5 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 5 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 6 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 6 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 7 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 7 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 8 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 8 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 9 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 9 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 10 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 10 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 11 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 11 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 12 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 12 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 13 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 13 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 14 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 14 out of 16 from process 1 out of 2 on exp-6-56
Hello from thread 15 out of 16 from process 0 out of 2 on exp-6-56
Hello from thread 15 out of 16 from process 1 out of 2 on exp-6-56
```

Outline

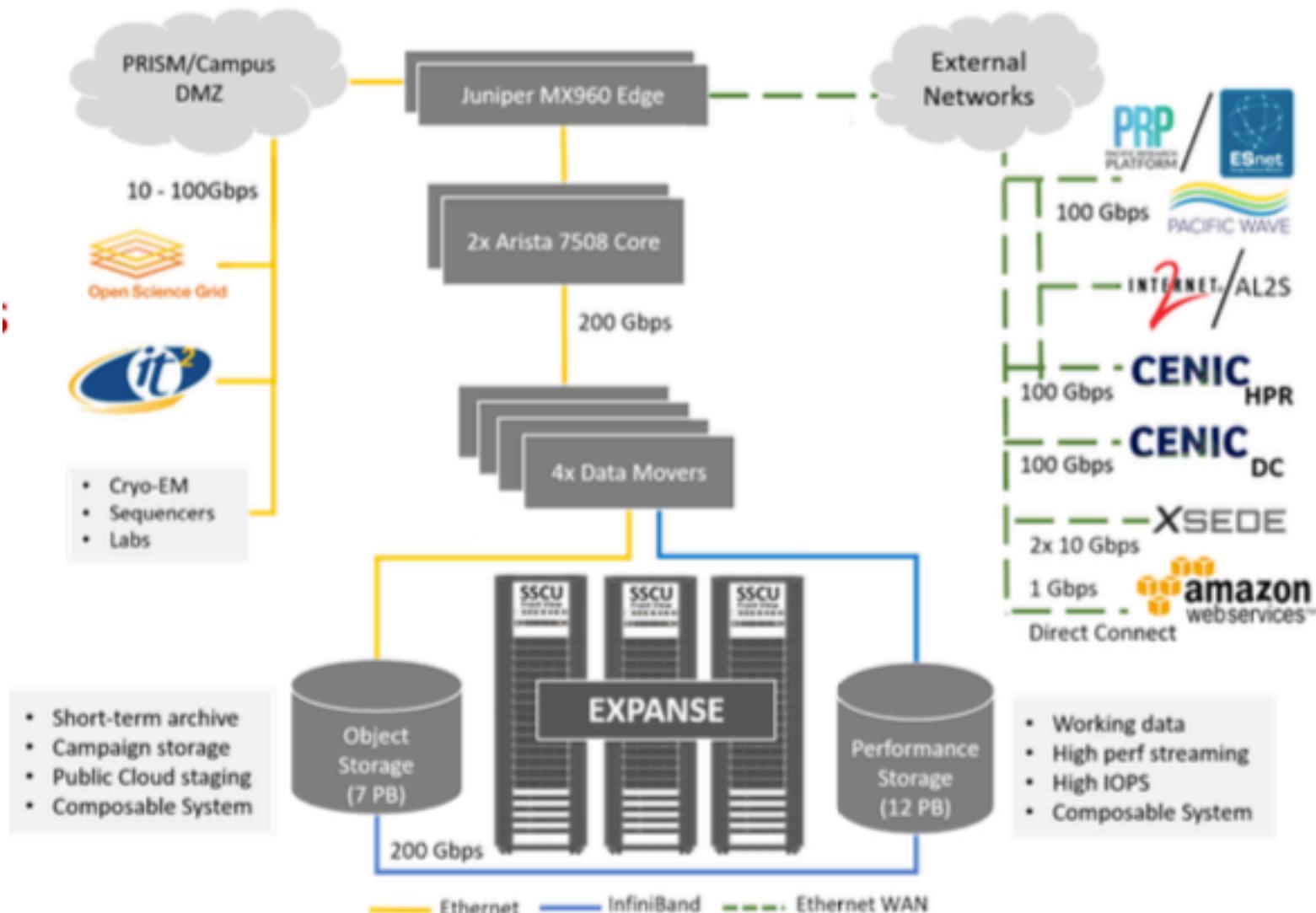
- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - MPI Jobs
 - OpenMP Jobs
 - GPU/CUDA Jobs
 - Hybrid MPI-OpenMP Jobs
- **Data and Storage**
- Final Comments

Data Centric Architecture

- Lustre parallel file system with 12 PB of usable capacity and 140 GB/s of bandwidth, 200k IOPS.
- Large fraction of the workload is dominated by many small files, the parallel file system will include multiple NVMe-based metadata servers and Lustre's Data on Metadata capability to achieve high I/O operations per second.
- Fast I/O Node-local, NVMe provides applications with extremely fast I/O.
- 7 PB of Ceph Object storage at SDSC for projects that need longer-term, archive-like capability over the life of their allocations.

DISK I/O Subsystem	
File Systems	NFS, Ceph
Lustre Storage(performance)	12 PB
Ceph Storage	7 PB
I/O bandwidth (performance disk)	140 GB/s, 200K IOPs

Expanse Connectivity Fabric



Facilitates Compute and Data Workflows

Home File System

- After logging in, users are placed in their home directory, /home, also referenced by the environment variable \$HOME.
- The home directory is limited in space and should be used only for source code storage.
- Users will have access to 100GB in /home.
- Jobs should **never** be run from the home file system, as it is not set up for high performance throughput.
- Users should keep usage on \$HOME under 100GB.
- Backups are currently being stored on a rolling 8-week period.

Parallel Lustre Filesystems

- Global parallel filesystem:
 - 12 PB Lustre parallel file system
 - 7 PB Ceph Object Store system
 - 140 GB/second performance storage.
- The two Lustre filesystems available on Expanse are:
 - Lustre Expanse scratch filesystem: /expanse/lustre/scratch/\$USER/
 - Lustre NSF projects filesystem: /expanse/lustre/projects/
- SDSC limits the number of files that can be stored in /lustre/scratch filesystem to 2 million files per user.
- Users should contact user support for assistance at help@xsede.org, if their workflow requires extensive small I/O, to avoid causing system issues associated with load on the metadata server.

Local Scratch

- Compute nodes have access to fast flash storage.
 - 1TB of SSD space available on each node.
 - The large memory nodes have 3.2TB of NVMe.
- GPU nodes have 1.6TB of NVMe.
- Latency to the SSDs is several orders of magnitude lower than that for spinning disk (<100 microseconds vs. milliseconds)
 - ideal for user-level check pointing and applications that need fast random I/O to large scratch files.
- Users can access the SSDs only during job execution under the following directories local to each compute node:
`/scratch/$USER/job_$SLURM_JOB_ID`
- A limited number of nodes in the "compute" partition have larger SSDs:
 - total of 1464 GB available in local scratch.
- They can be accessed by adding the following to the Slurm script:
`#SBATCH --constraint="large_scratch"`
-

Globus Endpoints, Data Movers and Mount Points

- All of Expanse's NFS and Lustre filesystems are accessible via the Globus endpoint **xsede#expanse**.
- The servers also mount Comets's filesystems, so the mount points are a different for each system.
- Table shows the mount points on the data mover nodes (that are the backend for **xsede#comet** and **xsede#expanse**).

Machine	Location on machine	Location on Globus/Data Movers
Expanse	/home/\$USER	/home/\$USER
Expanse	/expanse/lustre/projects	/expanse/lustre/projects/
Expanse	/expanse/lustre/scratch	/expanse/lustre/scratch/...
Comet	/oasis/projects/nsf	/oasis/projects/nsf
Comet	/oasis/scratch/comet	/oasis/scratch

For more information, see: <https://www.globus.org/how-it-works>

Outline

- Expanse Overview & Innovative Features
- Getting Started
- Modules
- Account Management
- Compiling and Linking Code
- Running Jobs
- Hands-on Examples
 - GPU/CUDA Jobs
 - OpenMP Jobs
 - MPI Jobs
 - Hybrid MPI-OpenMP Jobs
 - Large Memory
- Data and Storage
- Software
- Final Comments

Yes, You are Correct: Running Jobs on HPC Systems is Complex

- Multiple layers of hardware and software affect job performance
- Learn to develop and test in a modular fashion
- Build up a suite of test cases:
 - When things go wrong, make sure you can run simple test cases (HelloWorld).
 - This can eliminate questions about your environment.
- Consider using a code repository
 - When things go wrong, you can get back to a working version
- If you need help/have questions, contact XSEDE help desk:
 - **They are very helpful and respond quickly**
 - Support users around the world, so they are truly a 7/24 service
 - Avoid wasting your time.

When Things Go Wrong, Check Your User Environment

- Do you have the right modules loaded?
- What software versions do you need?
- Is your code compiled and updated
 - Did you compile it last year? Have the libraries changed?
- Are you running your job from the right location?
 - \$HOME versus \$WORK?

Run jobs from the right location

- Lustre scratch filesystem:
 - /oasis/scratch/expanse/\$USER/temp_project
 - Preferred: Scalable large block I/O)
- Compute/GPU node local SSD storage:
 - /scratch/\$USER/\$SLURM_JOBID
 - Meta-data intensive jobs, high IOPs)
- Lustre projects filesystem:
 - /oasis/projects/nsf
- /home/\$USER:
 - Only for source files, libraries, binaries.
 - *Do not* use for I/O intensive jobs.

Thank You

Resources

- Expanse User Guide
 - https://www.sdsc.edu/support/user_guides/expanse.html
- GitHub Repo for this webinar: clone code examples for this tutorial – clone example code:
 - <https://github.com/sdsc-hpc-training-org/expanse-101>
- SDSC Training Resources
 - https://www.sdsc.edu/education_and_training/training
 - <https://github.com/sdsc-hpc-training/webinars>
- XSEDE Training Resources
 - <https://www.xsede.org/for-users/training>
 - <https://cvw.cac.cornell.edu/expanse/>