Darshan: Enabling Insights into HPC I/O Behavior

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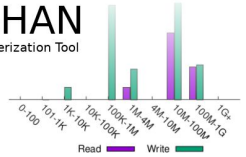
ECP Community BoF Days
May 12, 2022

BoF overview

DARSHAN
HPC I/O Characterization Tool



- The ability to characterize and understand application I/O workloads is critical to ensuring efficient use of an evolving and complex HPC I/O stack
  - Deep layers of coordinating I/O libraries and entirely new-to-HPC storage paradigms (e.g., object storage)
  - Emerging storage hardware (e.g., PMEM) and storage architectures (e.g., burst buffers)
- I/O analysis tools are invaluable in helping to navigate this complexity and to better understand I/O
  - Characterize I/O behavior of individual jobs to inform tuning decisions
  - Characterize job populations to better understand system-wide I/O stack usage and optimize deployments

BoF overview

In this BoF, we provide an overview of the Darshan I/O characterization tool and hear from guest speakers on exciting new Darshan instrumentation/analysis activities

Agenda:

- Darshan overview (Shane Snyder, ANL)
  - Background
  - Usage on ECP platforms
  - New and upcoming features
- AutoPerf instrumentation modules (Kevin Harms, ALCF)
- PyDarshan interface and tools (Nik Awtrey, LANL)
- Understanding I/O behavior with interactive Darshan log analysis (Jean Luca Bez, LBL)
- Free time: Q/A, audience-driven discussion

Darshan:
An application I/O characterization tool for HPC

What is Darshan?

- Darshan is a lightweight I/O characterization tool that captures concise views of HPC application I/O behavior
  - Produces a summary of I/O activity for each instrumented job
    - Counters, histograms, timers, & statistics
    - Full I/O traces (if requested)

- Widely available
  - Deployed (and commonly enabled by default!) at many HPC facilities around the world
- Easy to use
  - No code changes required to integrate Darshan instrumentation
  - Negligible performance impact; just “leave it on”
- Modular
  - Adding instrumentation for new I/O interfaces or storage components is straightforward

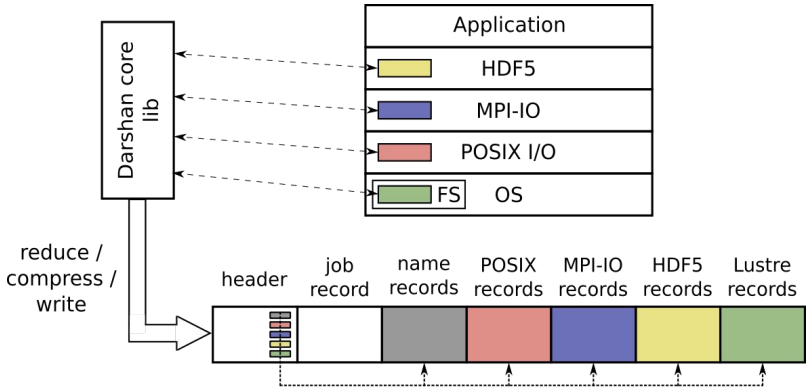
https://www.mcs.anl.gov/research/projects/darshan/
https://github.com/darshan-hpc/darshan

How does Darshan work?

DARSHAN
HPC I/O Characterization Tool

- Darshan can insert application I/O instrumentation at link-time (for static and dynamic executables) or at runtime using LD_PRELOAD (for dynamic executables)
  - Starting in version 3.2.0, Darshan supports instrumentation of any dynamically-linked executable (MPI or not) using the LD_PRELOAD method

- Darshan records file access statistics for each process as app executes
- At app shutdown, collect, aggregate, compress, and write log data
- After job completes, analyze Darshan log data
  - `darshan-job-summary` - provides a summary PDF characterizing application I/O behavior
  - `darshan-parser` - provides complete text-format dump of all counters in a log file
  - *`PyDarshan`* - Python analysis module for Darshan logs



Using Darshan on ECP platforms

Using Darshan on Cori (NERSC) and Theta (ALCF)

MPI applications

- Darshan is already installed and enabled by default on Cori and Theta Cray XC40 systems
  - Instrumentation enabled using software module that injects Darshan linker options when compiling MPI applications using Cray compiler wrappers (cc, CC, etc.)

```
ssnyder@cori10:~> module list
Currently Loaded Modulefiles:
  1) modules/3.2.11.4
  2) darshan/3.3.1
  3) craype-network-aries
  4) intel/19.1.2.254
  5) craype/2.7.10
  6) cray-libsci/20.09.1
  7) udreg/2.3.2-7.0.3.1_3.7__g5f0d670
ssnyder@cori10:~> module load darshan
```

Use '**`module list`**' to confirm Darshan is actually loaded

Darshan 3.3.1 is the default version on Cori (3.3.0 on Theta)

If Darshan not loaded, you can always load manually using '**`module load`**'

Using Darshan on Cori (NERSC) and Theta (ALCF)

DARSHAN
HPC I/O Characterization Tool

MPI applications

- OK, Darshan is loaded...now what?
  - Just compile and run your application!
  - Darshan inserts instrumentation directly into executable, regardless of linking mode
- LD_PRELOAD is another option for dynamically-linked executables:
  - This method is necessary for Python environments (i.e., mpi4py, h5py)
  - Also helpful for applications that cannot be recompiled

```
ssnyder@cori09:~> module show darshan
-------------------------------------------------------------------
/global/common/software/nersc/cle7up03/extra_modulefiles/darshan/3.3.1:

conflict         darshan
module-whatis    a scalable HPC I/O characterization tool
setenv           DARSHAN_BASE_DIR /global/common/cori_cle7up03/software/darshan/3.3.1
prepend-path     PATH /global/common/cori_cle7up03/software/darshan/3.3.1/bin
prepend-path     LD_LIBRARY_PATH /global/common/cori_cle7up03/software/darshan/3.3.1/lib
prepend-path     PKG_CONFIG_PATH /global/common/cori_cle7up03/software/darshan/3.3.1/lib/
pkgconfig
ssnyder@cori09:~> export LD_PRELOAD=/global/common/cori_cle7up03/software/darshan/3.3.1/l
ib/libdarshan.so
```

Manually set LD_PRELOAD to point to Darshan's shared library before running your application

Using Darshan on Summit (OLCF)

MPI applications

- Summit is an IBM Power9-based system that uses dynamic linking by default
  - Like Cori/Theta, software modules used to enable Darshan instrumentation
  - LD_PRELOAD mechanism used to interpose Darshan instrumentation libraries at runtime – no recompile needed!

```
[ssnyder@login4.summit ~]$ module list

Currently Loaded Modules:
  1) xl/16.1.1-10                      5) darshan-runtime/3.3.0-lite
  2) spectrum-mpi/10.4.0.3-20210112    6) xalt/1.2.1
  3) lsf-tools/2.0                     7) DefApps
  4) hsi/5.0.2.p5
```

Summit also provides '**`module list`**' command

Darshan 3.3.0 is the default version on Summit, '-lite' just means this module has no HDF5 support

Note: darshan-runtime and darshan-util are separate modules, with only darshan-runtime loaded by default

Finding Darshan log files

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- After the application terminates, look for your log files:

Darshan logs typically stored in a central directory for all users for system-wide deployments, use '**`darshan-config --log-path`**' to find

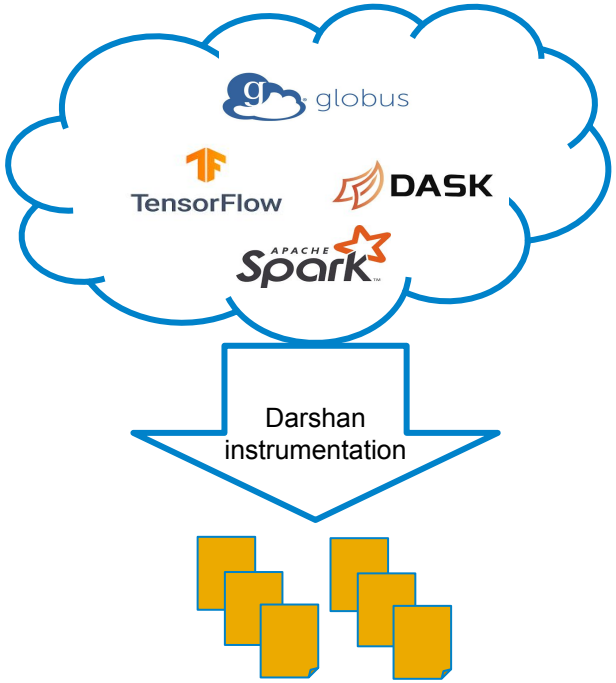
```
ssnyder@cori01:~> darshan-config --log-path
/global/cscratch1/sd/darshanlogs
ssnyder@cori01:~> cd /global/cscratch1/sd/darshanlogs
ssnyder@cori01:/global/cscratch1/sd/darshanlogs>
ssnyder@cori01:/global/cscratch1/sd/darshanlogs> cd 2021/3/4
ssnyder@cori01:/global/cscratch1/sd/darshanlogs/2021/3/4> ls | grep snyder | cat
ssnyder_mpi-io-test_id40245367_3-4-50083-3517743081787486417_1614894884.darshan
```

Logs further indexed using '*year/month/day*' the job executed.

Log file name starts with the following pattern: '*username_exename_jobid*…'

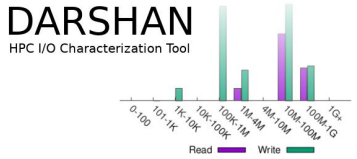
Using Darshan with non-MPI applications

- Starting in version 3.2.0, Darshan supports instrumentation of non-MPI applications using LD_PRELOAD (i.e., dynamically-linked binaries)
  - Users must additionally export '**`DARSHAN_ENABLE_NONMPI=1`**' to enable this mode
- **NOTE**: With Darshan's non-MPI environment set, log files will be generated for every invoked process
  - Instrumentation scope can be limited to specific commands using: '`env DARSHAN_ENABLE_NONMPI=1 cmd <args>`'
  - Darshan runtime configuration parameters (which we will cover later) can help limit instrumentation to specific application names



Analyzing Darshan logs

Analyzing Darshan logs



➢ After generating and locating your log, use Darshan analysis tools to inspect log file data:

```
snyder@thetalogin5:/lus/theta-fs0/logs/darshan/theta/2020/1/22> cp snyder_
mpi-io-test_id403177_1-22-74255-16539625359987666393_1.darshan ~/tmp/
snyder@thetalogin5:/lus/theta-fs0/logs/darshan/theta/2020/1/22> cd ~/tmp/
snyder@thetalogin5:~/tmp> darshan-parser snyder_mpi-io-test_id403177_1-22-
74255-16539625359987666393_1.darshan
```

Copy the log file somewhere else for analysis

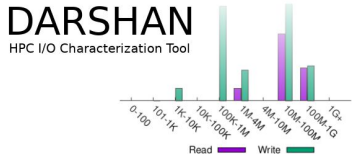
Invoke `darshan-parser` to get detailed counters

```
#<module>       <rank>  <record id>      <counter>       <value> <file name>
POSIX   -1      3675075178343058238     POSIX_OPENS     16      /gpfs/mira-home/
POSIX   -1      3675075178343058238     POSIX_READS     4       /gpfs/mira-home/
POSIX   -1      3675075178343058238     POSIX_WRITES    4       /gpfs/mira-home/
POSIX   -1      3675075178343058238     POSIX_SEEKS     6       /gpfs/mira-home/

MPI-IO  -1      3675075178343058238     MPIIO_INDEP_OPENS       8       /gpfs/mi
MPI-IO  -1      3675075178343058238     MPIIO_COLL_OPENS        0       /gpfs/mi
MPI-IO  -1      3675075178343058238     MPIIO_INDEP_READS       4       /gpfs/mi
MPI-IO  -1      3675075178343058238     MPIIO_INDEP_WRITES      4       /gpfs/mi
MPI-IO  -1      3675075178343058238     MPIIO_COLL_READS        0       /gpfs/mi
```

Modules use a common format for printing counters, indicating the corresponding module, rank, filename, etc. -- here sample counters are shown for both POSIX and MPI-IO modules

Analyzing Darshan logs



- But, `darshan-parser` output isn't so accessible for most users… use `darshan-job-summary` tool to produce summary PDF of app I/O behavior

```
snyder@thetalogin5:~/tmp> module load texlive
snyder@thetalogin5:~/tmp>
snyder@thetalogin5:~/tmp> darshan-job-summary.pl snyder_mpi-io-test_id403177_1-2
2-74255-16539625359987666393_1.darshan
Pod::LaTeX will be removed from the Perl core distribution in the next major rel
ease. Please install it from CPAN. It is being used at /soft/perftools/darshan/d
arshan-3.1.5/lib/TeX/Encode.pm, line 10.
Slowest unique file time: 0.000295
Slowest shared file time: 0.480483
Total bytes read and written by app (may be incorrect): 134218370
Total absolute I/O time: 0.480778
**NOTE: above shared and unique file times calculated using MPI-IO timers if MPI
-IO interface used on a given file, POSIX timers otherwise.
snyder@thetalogin5:~/tmp>
snyder@thetalogin5:~/tmp> ls | grep darshan
snyder_mpi-io-test_id403177_1-22-74255-16539625359987666393_1.darshan
snyder_mpi-io-test_id403177_1-22-74255-16539625359987666393_1.darshan.pdf
```

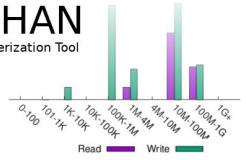
On Theta, texlive module is needed for generating PDF summaries -- may not be needed on other systems

Invoke `darshan-job-summary` on log file to produce PDF

A few simple statistics (total I/O time and volume) are output on command line

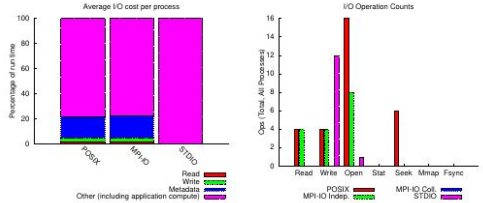
Output PDF file name based on Darshan log file name

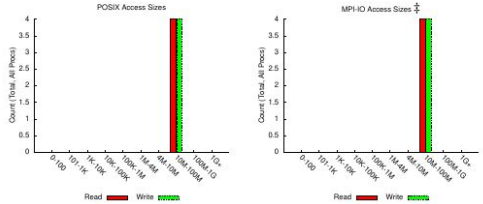
Analyzing Darshan logs



jobid: 403177	uid: 31074	nprocs: 4	runtime: 2 seconds

I/O performance *estimate* (at the MPI-IO layer): transferred 642 MiB at 266.40 MiB/s
I/O performance *estimate* (at the STDIO layer): transferred 0.0 MiB at 2.08 MiB/s





Most Common Access Sizes
(POSIX or MPI-IO)

	access size	count
POSIX	16777216	8
MPI-IO ‡	16777216	8

‡ NOTE: MPI-IO accesses are given in terms of aggregate datatype size.

File Count Summary
(estimated by POSIX I/O access offsets)

type	number of files	avg. size	max size
total opened	2	33M	64M
read-only files	0	0	0
write-only files	1	642	642
read/write files	1	64M	64M
created files	2	33M	64M

Result is a multi-page PDF containing graphs, tables, and performance estimates characterizing the I/O workload of the application

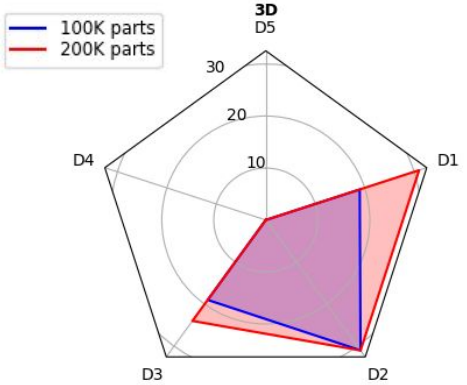
What's new in Darshan?

HDF5 instrumentation modules

Available in Darshan 3.2.0+ versions

- HDF5 offers application scientists a convenient abstraction for large data collections
  - But, it can be difficult to understand interactions with lower layers of the I/O stack that most impact performance

- To better understand HDF5 usage and performance, we have developed Darshan instrumentation modules for HDF5 file (H5F) and dataset (H5D) APIs
  - What are file and dataset properties?
  - How are datasets organized within files?
  - How are datasets accessed?
  - Do HDF5 accesses decompose efficiently to lower-level accesses? If not, do any optimizations make sense?

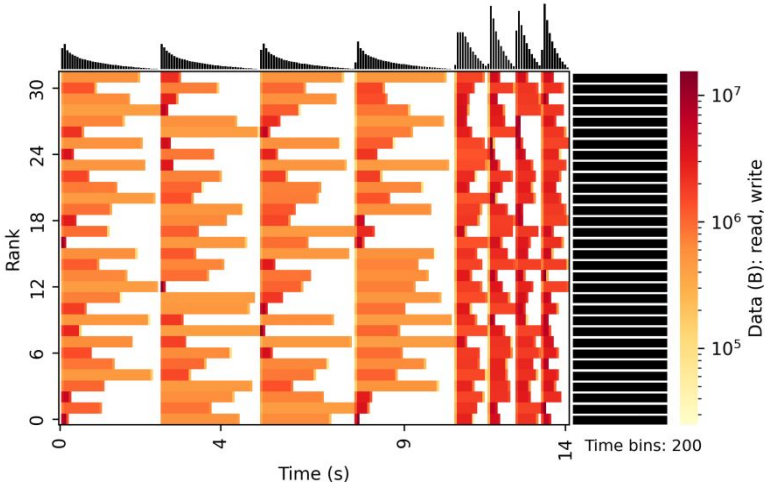


Number of elements accessed in each dataset dimension for the most common access for MACSio benchmark runs. For optimal performance, access dimensions should match any HDF5 chunking settings

Darshan runtime heatmaps

Available in Darshan 3.4.0+ versions

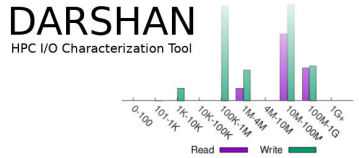
- Traditional Darshan instrumentation captures coarse-grained I/O timing info (start/end timestamps for open, read, write, close operations)
  - DXT tracing can be enabled for fine-grained details, but storing details of every I/O operation would be an expensive *default* mode for Darshan
- To address this, we have implemented runtime I/O heatmaps to capture per-process histograms of I/O activity
  - Histograms are a fixed size, with bins being resized as the app executes
  - Heatmaps for POSIX, MPI-IO, and STDIO interfaces are currently supported



Heatmaps can quickly provide users insight into how I/O intensity varies over time, ranks, and I/O interfaces

Darshan runtime library configuration

Available in Darshan 3.4.0+ versions



- Motivated by persistent user reports of Darshan exhausting memory, new comprehensive runtime library configuration mechanisms have been implemented:
  - Environment variables
  - Config files
- Allow runtime control over the following:
  - Enabled/disabled modules
  - Number of records to allocate for each module
  - Record name exclusion/inclusion regexes
  - App name exclusion/inclusion regexes
  - Total Darshan memory for module data (MODMEM) and name records (NAMEMEM)
- Enable facilities to fine-tune Darshan behavior after it has been deployed

```
# enable DXT modules, which are off by default
MOD_ENABLE      DXT_POSIX,DXT_MPIIO

# allocate 4096 file records for POSIX and MPI-IO modules
# (darshan only allocates 1024 per-module by default)
MAX_RECORDS     4096      POSIX,MPI-IO

# the '*' specifier can be used to apply settings for all modules
# in this case, we want all modules to ignore record names
# prefixed with "/home" (i.e., stored in our home directory),
# with a superseding inclusion for files with a ".out" suffix)
NAME_EXCLUDE    ^/home        *
NAME_INCLUDE    .out$         *

# bump up Darshan's default memory usage to 8 MiB
MODMEM  8

# avoid generating logs for git and ls binaries
APP_EXCLUDE     git,ls
```

Example Darshan config file to modify Darshan's memory usage and instrumentation scope

Other recent Darshan developments

- AutoPerf instrumentation modules (v3.3.0)
  - MPI communication characterization
  - Network counters for Cray XC systems
  - Contributions by Sudheer Chunduri
- Stable PyDarshan interface (v3.4.0)
  - Including first cut at a new job summary tool
  - Contributions by Nik Awtrey, Tyler Reddy, Jakob Luettgau
- Performance optimizations to improve overhead of Darshan wrappers, locks, and timers (v3.4.0)
- Adopted automake/libtool support for Darshan's build (v3.4.0)
  - Contribution by Wei-Keng Liao

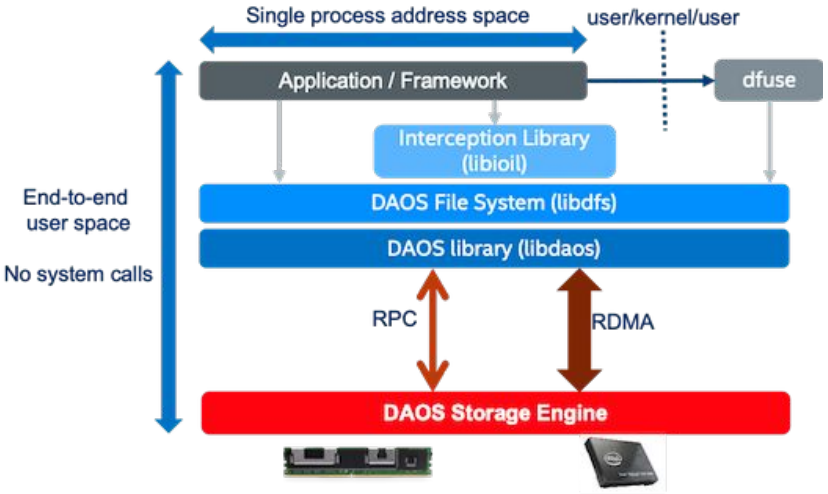
More about this shortly

Next up on the Darshan roadmap

DAOS instrumentation modules

- DAOS offers a novel storage paradigm for HPC apps: object-based storage over a combo of SCM and SSD devices
  - libdfs: DAOS's POSIX file system emulation API
  - libdaos: DAOS's native object (key-val) API
- Understanding usage/performance characteristics can be critical to realizing full system I/O potential
  - Development of Darshan instrumentation modules for DAOS is in progress and should be ready for release soon

DFS module available for experimental use:
https://github.com/darshan-hpc/darshan/pull/739

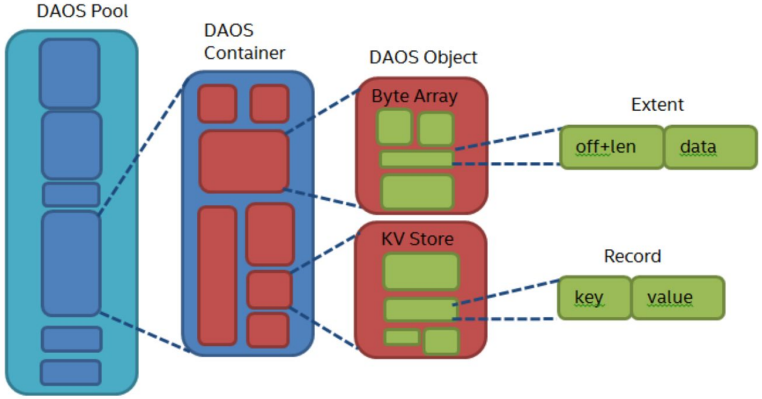


DAOS I/O stack for HPC applications and I/O middleware.

Figure courtesy of Intel

DAOS instrumentation modules

- The file-based DFS interface is a natural fit for Darshan's traditional instrumentation strategy (per-file I/O statistics)
  - Design follows closely that of Darshan's POSIX module, as you would expect
- On the other hand, a Darshan instrumentation module for the DAOS object interface poses a major challenge:
  - How can Darshan succinctly capture access details for objects that are key-vals?
  - Key access patterns will be critical to understanding how DAOS objects are used in the wild



DAOS object storage model. Objects can either be byte arrays or entire key-val stores.

Figure courtesy of Intel

We are still investigating what characteristics about key access patterns to capture and are seeking feedback from early DAOS users

Other next steps for Darshan

- Increase instrumentation coverage
  - Support more APIs (e.g., PnetCDF, currently in a PR)
  - Extend DXT tracing capabilities to new APIs (HDF5, STDIO, etc.)
- Iterate more on PyDarshan-based log analysis tools
  - Methods to extract actionable I/O insights from raw log data
    - "*looks like your Lustre striping parameters were poorly chosen, consider doing X*"
  - Workflow-aware log analysis utilities
    - Existing tools operate on single jobs, but workflows are foundational to HPC and warrant deeper understanding

This research was supported by the Exascale Computing Project (17-SC-20-SC), a joint project of the U.S. Department of Energy's Office of Science and National Nuclear Security Administration, responsible for delivering a capable exascale ecosystem, including software, applications, and hardware technology, to support the nation's exascale computing imperative.