ARGONNE
ATPESC2024
EXTREME-SCALE COMPUTING

How to Understand and Tune HPC I/O Performance

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August 8, 2024

Surveying the HPC I/O landscape

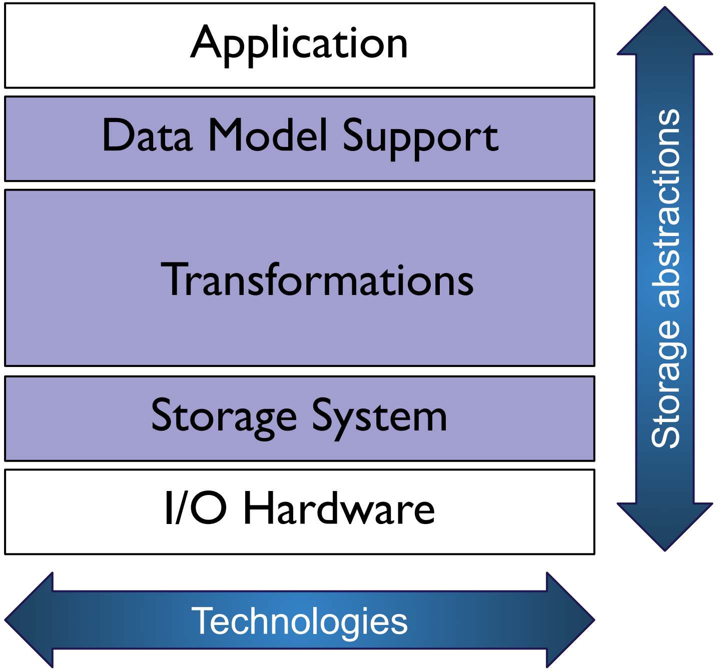
A complex data management ecosystem

As evidenced by today's presentations, the HPC I/O landscape is deep and vast:

- High-level data abstractions: HDF5, PnetCDF
- I/O middleware: MPI-IO
- Storage systems: Lustre, GPFS, DAOS
- Storage hardware: HDDs, SSDs, SCM

HPC applications themselves are evolving and encountering new data management challenges.

Understanding I/O behavior in this environment is difficult, much less turning observations into actionable I/O tuning decisions.



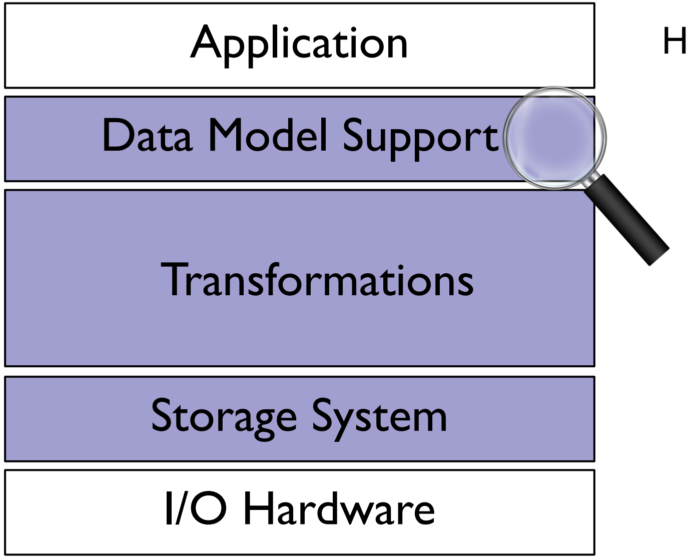
Hands on exercises:
https://github.com/radix-io/hands-on

Characterizing HPC I/O workloads with Darshan

A look under the hood of an HPC application

You have already heard some basics about Darshan, a powerful tool for users to better understand and tune their I/O workloads.

Darshan provides many helpful stats across multiple layers of the I/O stack that are critical to understanding application I/O behavior.



HDF5 stats*:

- Accessed files/datasets
- Operation counts
- Total read/write volumes
- Common access info (including details of hyperslab accesses)
- Chunking parameters
- Dataset dimensionality and size
- MPI-IO usage
- I/O timing

*Note: HDF5 instrumentation is not typically enabled for facility Darshan installs – you will need to install this version yourself.

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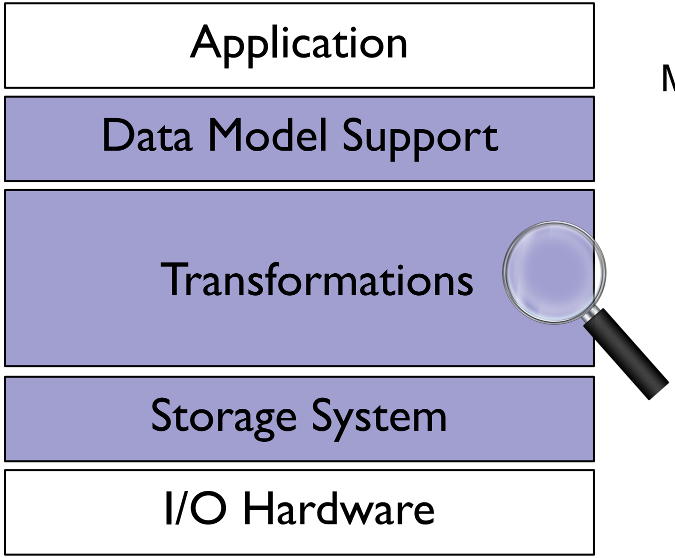

MPI-IO stats:

- Operation counts (open, read, write, sync)
- Collective and independent I/O usage
- Total read/write volumes
- Access size info
  - Common values
  - Histograms
- I/O timing

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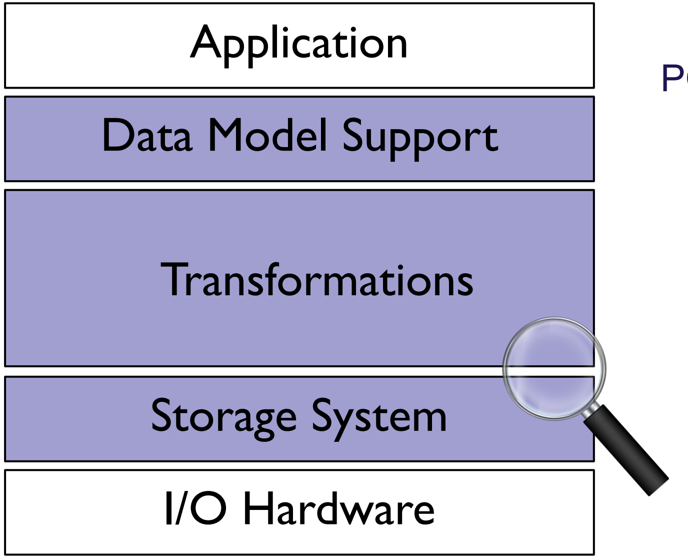

POSIX stats:

- Operation counts (open, read, write, seek, stat)
- Total read/write volumes
- File alignment
- Access size/stride info
  - Common values
  - Histograms
- I/O timing

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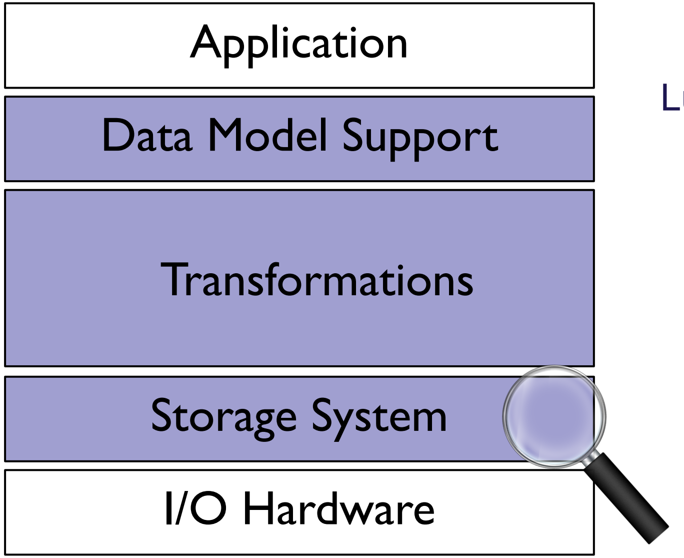

Lustre stats:

- Data server (OST) and metadata server (MDT) counts
- Stripe size/width
- OST list serving a file

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Characterizing HPC I/O workloads with Darshan

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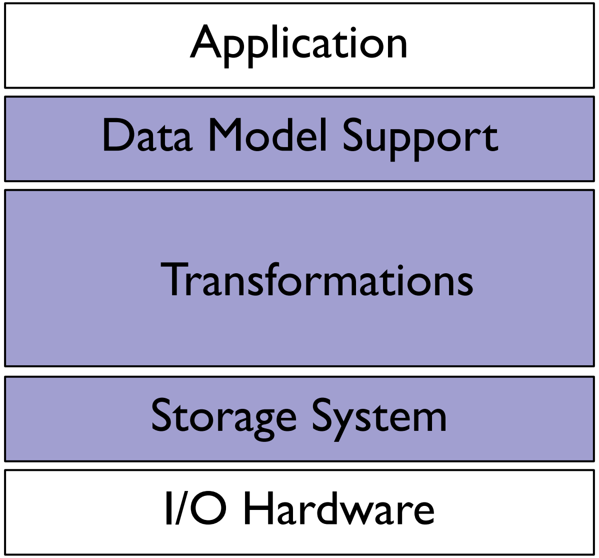

Let's see how Darshan can be leveraged in some practical use cases that demonstrate general best practices in tuning HPC I/O performance.

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Tuning the storage system

Ensuring storage resources match application I/O needs

For some parallel file systems like Lustre, users have direct control over file striping parameters.

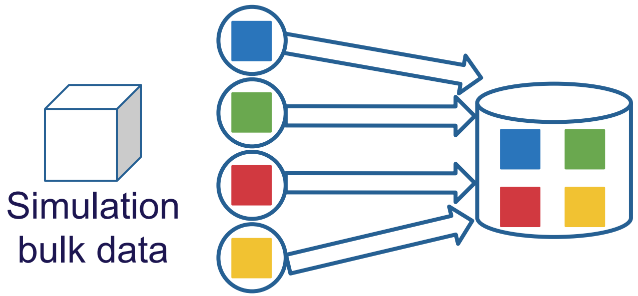
Bad news: Users may have to have some knowledge of the file system to get good I/O performance.

Good news: Users can often get higher I/O performance than system defaults with thoughtful tuning -- file systems aren't perfect for every workload!

Tuning the storage system

Ensuring storage resources match application I/O needs

Tuning decisions can and should be made independently for different file types.



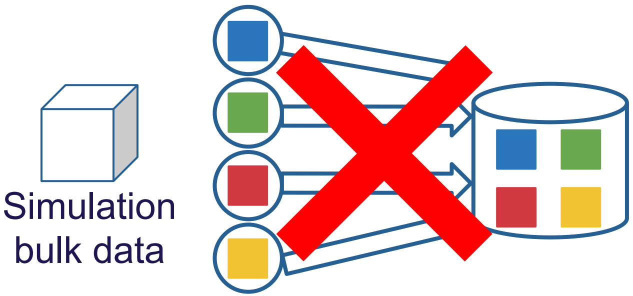
Simulation clients write data to 1 storage server.

Tuning the storage system

Ensuring storage resources match application I/O needs

Tuning decisions can and should be made independently for different file types.

Large application datasets should ideally be distributed across as many storage resources as possible.



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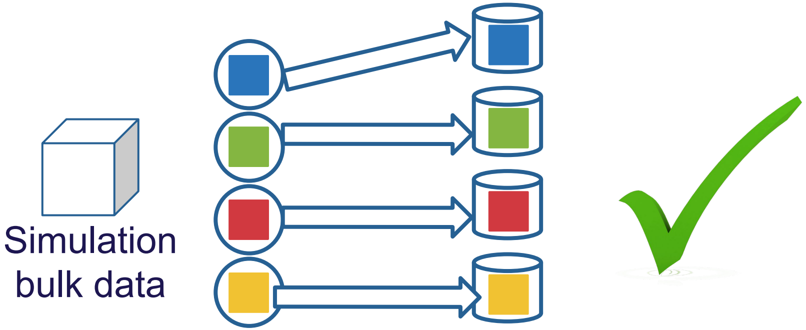

Simulation clients load balance writes across multiple servers.

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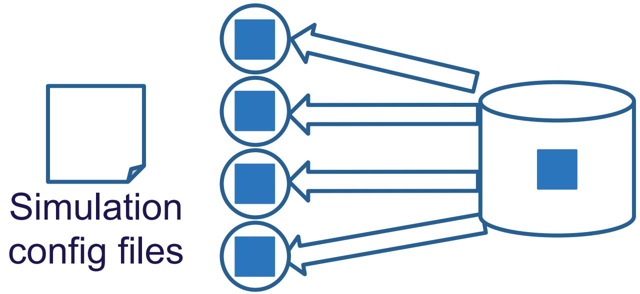
Ensuring storage resources match application I/O needs

Tuning decisions can and should be made independently for different file types.

On the other hand, smaller files often benefit from being stored on a single server.



Simulation clients read config data from 1 storage server.

Tuning the storage system

Ensuring storage resources match application I/O needs

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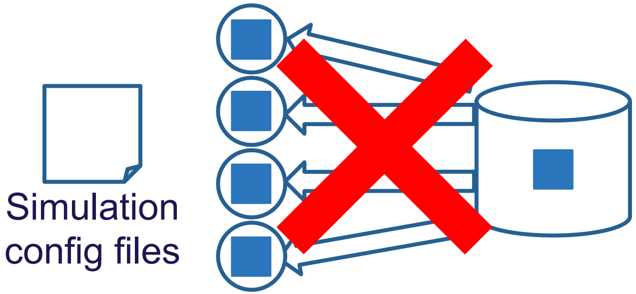
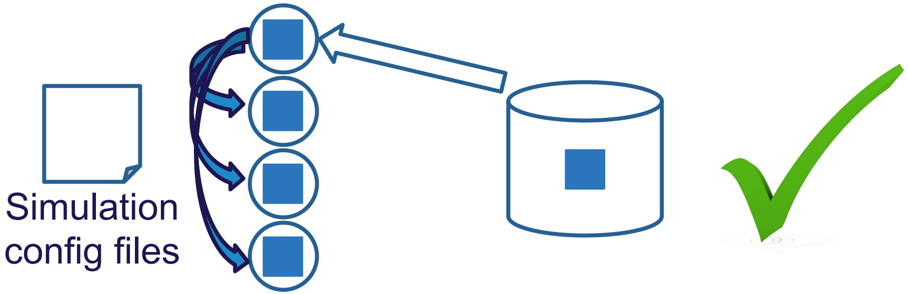
On the other hand, smaller files often benefit from being stored on a single server.



Simulation clients read config data from 1 storage server.



Better yet, limit storage contention by having 1 client read data and distribute using communication (e.g., MPI).

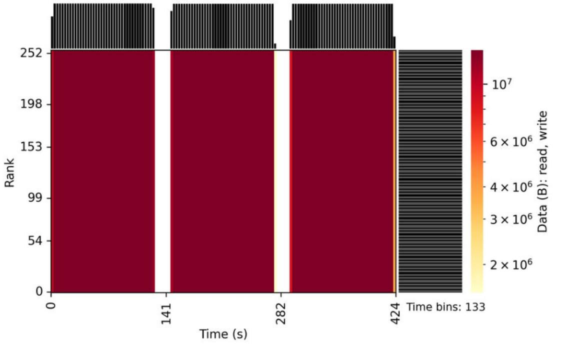
Tuning the storage system

Ensuring storage resources match application I/O needs

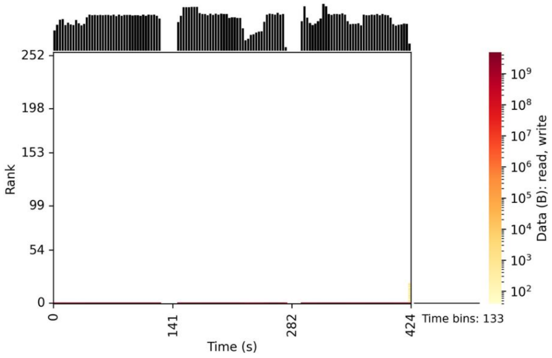
Be aware of what file system settings are available to you and don't assume system defaults are always the best… you might be surprised what you find.

- ALCF Polaris and NERSC Perlmutter Lustre scratch file systems both have a default stripe width of 1 (i.e., files are stored on one server).

MPI-IO



POSIX



256 process (4 node) h5bench[1] runs on NERSC Perlmutter.

h5bench contains lots of parameters for controlling characteristics of generated HDF5 workloads.

1. https://github.com/hpc-io/h5bench

Tuning the storage system

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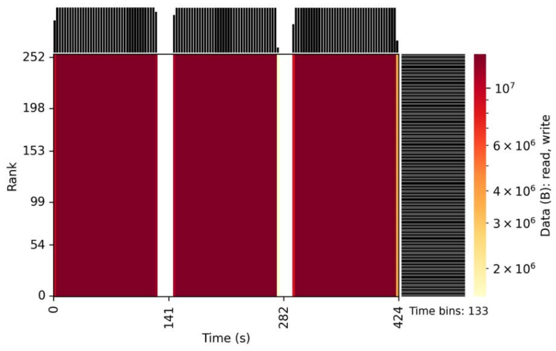
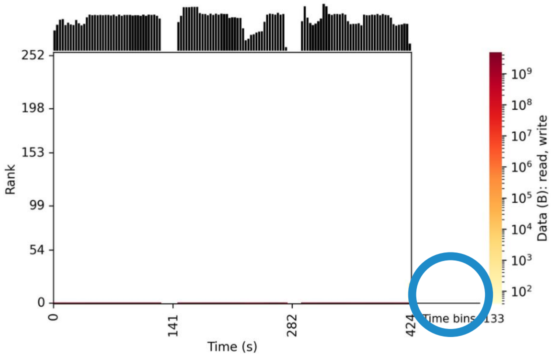


POSIX

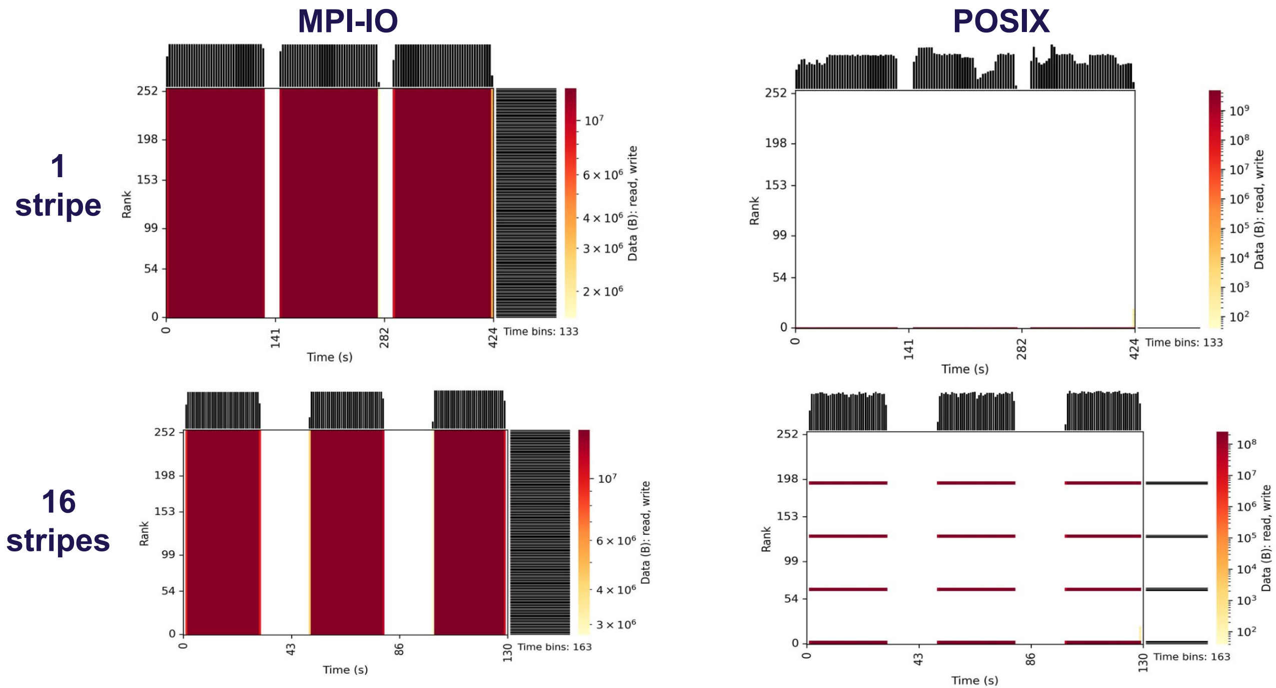


All I/O is funneled through rank 0.

MPI-IO collective I/O driver for Lustre assigns dedicated aggregator processes for each stripe, yielding a single aggregator for files of 1 stripe.

Tuning the storage system

Ensuring storage resources match application I/O needs



Manually setting the stripe width to 16 yields more I/O aggregators and better performance:

```
> lfs setstripe -c 16 testFile
```


Hands on exercises: https://github.com/radix-io/hands-on

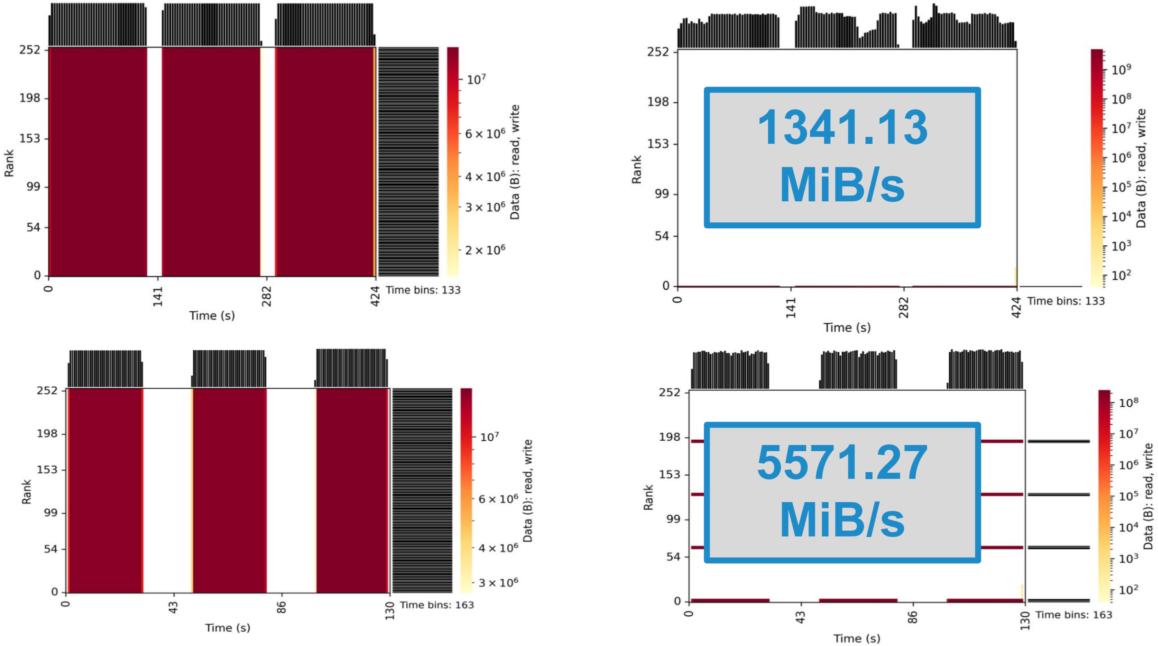
Tuning the storage system

Ensuring storage resources match application I/O needs

MPI-IO | POSIX

1 stripe

16 stripes



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> lfs setstripe -c 16 testFile
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4x performance improvement!

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Tuning the storage system

Ensuring storage resources match application I/O needs

Consult facilities documentation for established best practice!

Suggestions

- File Per Process
  - Use default stripe count of 1
  - Use default stripe size of 1MB
- Shared File
  - Use 48 OSTs per file for large files > 1 GB
  - Experiment with larger stripe sizes between 8 and 32MB
  - Collective buffer size will set to stripe size
- Small File
  - Use default stripe count of 1
  - Use default stripe size of 1MB

	Single Shared-File I/O	File per Process
File size	Command	Command
< 1 GB	keep default striping	keep default striping
1 - 10 GB	`stripe_small`	keep default striping
10 - 100 GB	`stripe_medium`	keep default striping
100 GB - 1 TB	`stripe_large`	keep default striping
> 1 TB	`stripe_large`	`stripe_large`

ALCF (left) and NERSC (right) docs providing suggestions/commands for properly striping different types of files (i.e., small vs large, file-per-process vs shared file)

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Tuning the storage system

Ensuring storage resources match application I/O needs

Consult facilities documentation for established best practice!

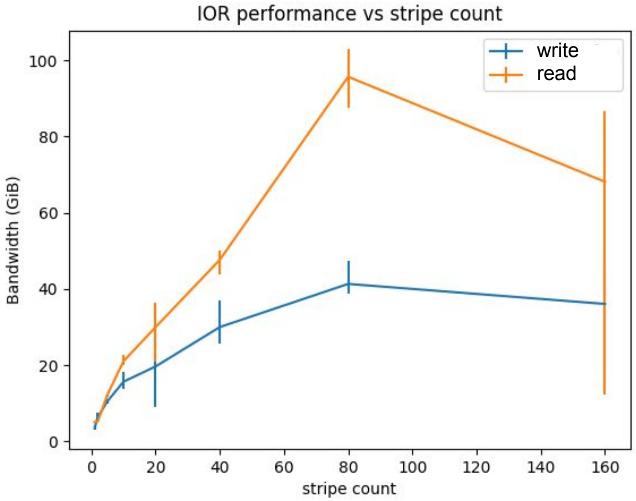
- The default striping set on Orion is targeted to work well for a variety of workloads
- In most cases, users should use this default striping. Though possible, manual striping should only occur after careful consideration and under collaboration with OLCF staff
- The default striping policy may change due to findings in production

OLCF presentation on Orion storage system detailing usage of Lustre's new progressive file layout mechanism

Tuning the storage system

Ensuring storage resources match application I/O needs

Consult facilities documentation for established best practice! Sometimes you may even need to experiment yourself.



128-node example of the IOR benchmark using various stripe counts on ALCF Polaris.

For more I/O intensive programs, it's typically better to err on the side of more storage servers. The following command stripes across all servers:

```
> lfs setstripe -c -1 testFile
```

https://github.com/radix-io/io-sleuthing/tree/main/examples/striping

Tuning low-level (POSIX) file I/O

Making efficient use of a no-frills I/O API

Users may also need to pay close attention to file system alignment when issuing I/O accesses to a file.

- Accesses that are not aligned can introduce performance inefficiencies on file systems.

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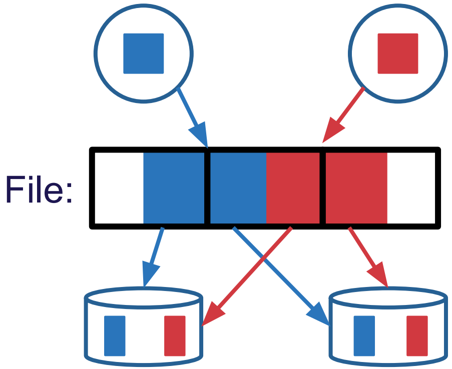
For Lustre, performance can be maximized by aligning I/O to stripe boundaries:



Unaligned I/O requests can span multiple servers and introduce inefficiencies in storage protocols.

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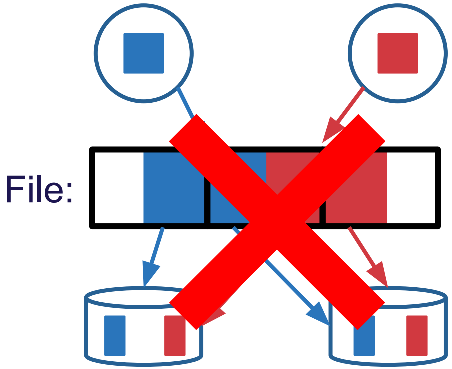
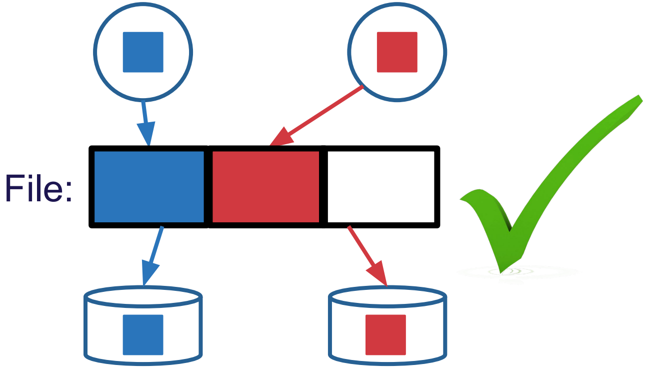


Instead, ensure client accesses are well-aligned to avoid Lustre server contention.



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Tuning low-level (POSIX) file I/O

Making efficient use of a no-frills I/O API

Consider a simple 10-process (10-node) NERSC Cori example where processes write in an interleaved fashion to a single shared file:

aligned

# Module	Rank	Wt/Rd	Segment	Offset	Length	Start(s)	End(s)	[OST]
X_POSIX	0	write	0	0	1048576	0.0054	0.0066	[197]
X_POSIX	0	write	1	10485760	1048576	0.0066	0.0073	[197]
X_POSIX	0	write	2	20971520	1048576	0.0073	0.0081	[197]
X_POSIX	0	write	3	31457280	1048576	0.0081	0.0088	[197]

Use Darshan's DXT tracing module to get details about each individual write access – **more details on DXT usage coming soon.**

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X_POSIX	0	write	3	31457280	1048576	0.0081	0.0088	[197]

Each access is aligned to the Lustre stripe size (1 MiB).

Each process interacts with a single Lustre server (OST).

Tuning low-level (POSIX) file I/O

Making efficient use of a no-frills I/O API

Consider a simple 10-process (10-node) NERSC Cori example where processes write in an interleaved fashion to a single shared file:

unaligned

# Module	Rank	Wt/Rd	Segment	Offset	Length	Start(s)	End(s)	[OST]	
X_POSIX	0	write	0	524288	1048576	0.0065	0.0594	[32]	[197]
X_POSIX	0	write	1	11010048	1048576	0.0594	0.1268	[32]	[197]
X_POSIX	0	write	2	21495808	1048576	0.1268	0.2060	[32]	[197]
X_POSIX	0	write	3	31981568	1048576	0.2060	0.2069	[32]	[197]

Each access spans two Lustre stripes due to unaligned offsets.

Each process interacts with two Lustre servers (OSTs).

Tuning low-level (POSIX) file I/O

Making efficient use of a no-frills I/O API

Even in this small workload, we pay a nearly **20% performance penalty when I/O accesses are not aligned** to file stripes (1 MB).

aligned

# Module	Rank	Wt/Rd	Segment	Offset	Length	Start(s)	End
X_POSIX	0	write	0	0	1048576	0.0054	
X_POSIX	0	write	1	10485760	1048576	0.0066	
X_POSIX	0	write	2	20971520	1048576	0.0073	
X_POSIX	0	write	3	31457280	1048576	0.0081	

380.28 MiB/s

unaligned

# Module	Rank	Wt/Rd	Segment	Offset	Length	Start(s)	End(s)
X_POSIX	0	write	0	524288	1048576	0.0065	0.05
X_POSIX	0	write	1	11010048	1048576	0.0594	0.12
X_POSIX	0	write	2	21495808	1048576	0.1268	0.20
X_POSIX	0	write	3	31981568	1048576	0.2060	0.20

310.14 MiB/s

Tuning low-level (POSIX) file I/O

Making efficient use of a no-frills I/O API

Accounting for subtle I/O performance factors like file alignment can be a painstaking process…

*As highlighted by other presentations, high-level I/O libraries like HDF5 and PnetCDF can help mask much of the complexity needed for transforming scientific computing I/O workloads into performant POSIX-level file system accesses – **don't reinvent the wheel, use high-level I/O libraries wherever you can!***

Tuning high-level (HDF5) data access

Optimizing application interactions with the I/O stack

Recall that HDF5 provides a chunking mechanism to partition user datasets into contiguous chunks in the underlying file.

- Users can greatly improve performance of partial dataset I/O operations by choosing chunking parameters that match expected access patterns.

Tuning high-level (HDF5) data access

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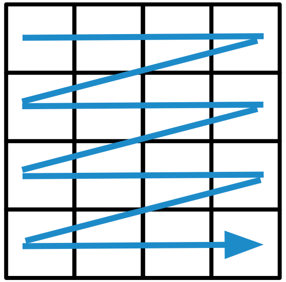

By default, HDF5 will store the dataset contiguously row-by-row (i.e., row-major format) in the file.

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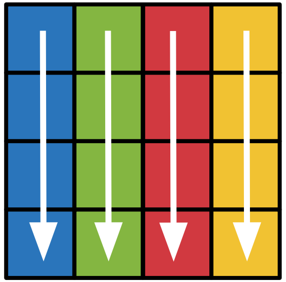
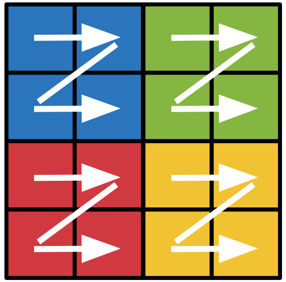


column-based



block-based

If dataset access patterns do not suit a simple row-major storage scheme, chunking can be applied to map chunks of dataset data to contiguous regions in the file.

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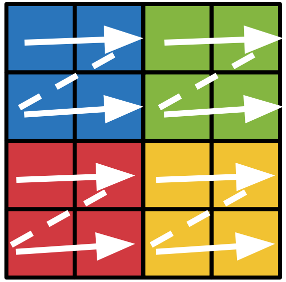
Tuning high-level (HDF5) data access

Optimizing application interactions with the I/O stack

Consider a 256-process (4-node) Polaris example where each process exclusively writes a 2048x2048 block of the dataset (32 MB per-process, 8 GB total):



With no chunking, each process must issue many smaller non-contiguous I/O requests (**solid lines**) and seek around the file (**dashed lines**), yielding low I/O performance.

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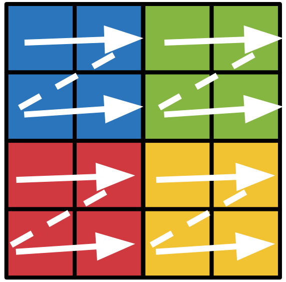
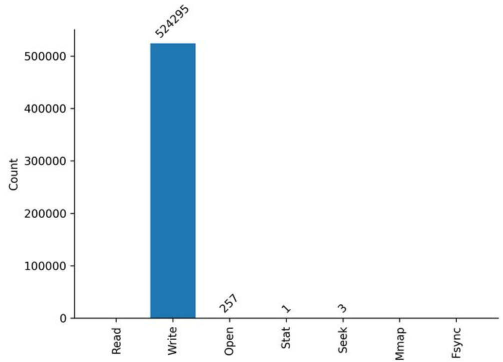
Tuning high-level (HDF5) data access

Optimizing application interactions with the I/O stack

Consider a 256-process (4-node) Polaris example where each process exclusively writes a 2048x2048 block of the dataset (32 MB per-process, 8 GB total):

I/O performance estimate	503.47 MiB/s (average)





Access Size	Count
16384	524288
96	2
328	1
544	1

256 individual HDF5 writes (1-per-process) yields 500K+ POSIX writes.

Tuning high-level (HDF5) data access

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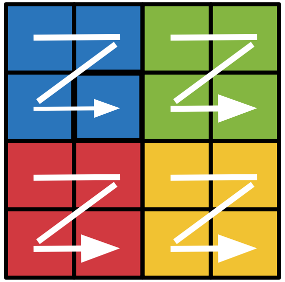

With chunking applied, each process can read their entire data block using one large, contiguous access in the file.

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Tuning high-level (HDF5) data access

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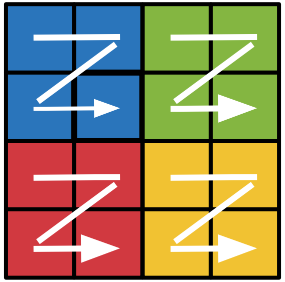
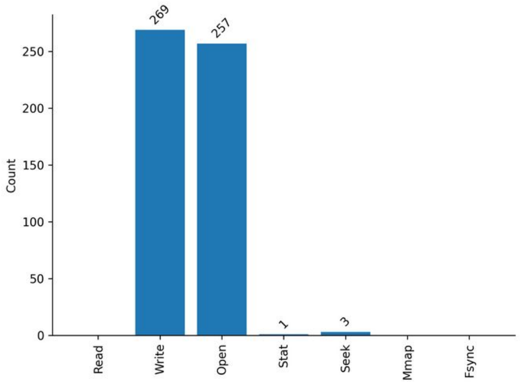
I/O performance estimate	1450.57 MiB/s (average)





Access Size	Count
33554432	256
2616	6
96	2
544	1

Chunking results in a much more manageable POSIX workload.

Nearly a 3x performance improvement!

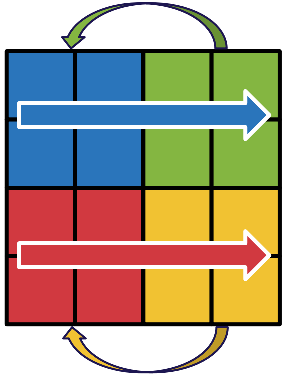
Hands on exercises:
https://github.com/radix-io/hands-on

Tuning high-level (HDF5) data access

Optimizing application interactions with the I/O stack

An alternative optimization forgoes chunking and uses collective I/O to improve the efficiency of this block-style data access.

- Rely on MPI-IO layer collective buffering algorithm to generate contiguous storage accesses and to limit number of clients interacting with storage system.



With collective I/O enabled, designated aggregator processes perform I/O on behalf of their peers, and communicate their data using MPI calls.

E.g., the green process sends its write data to the blue process (aggregator), who then writes both of their data in one big contiguous chunk.

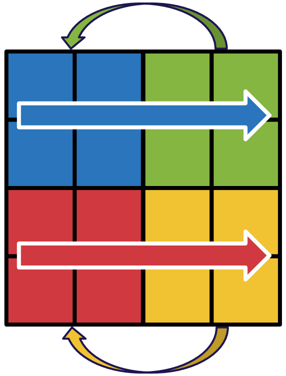
Hands on exercises: https://github.com/radix-io/hands-on

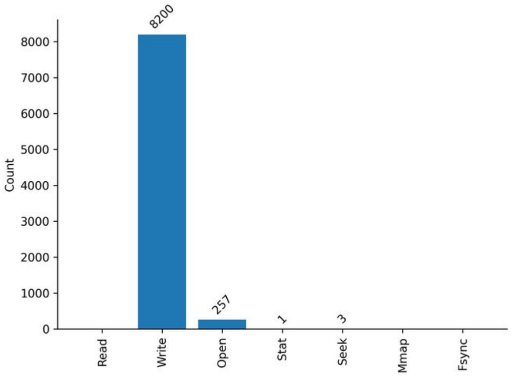
Tuning high-level (HDF5) data access

Optimizing application interactions with the I/O stack

Consider a 256-process (4-node) Polaris example where each process exclusively writes a 2048x2048 block of the dataset (32 MB per-process, 8 GB total):

I/O performance estimate	13124.01 MiB/s (average)





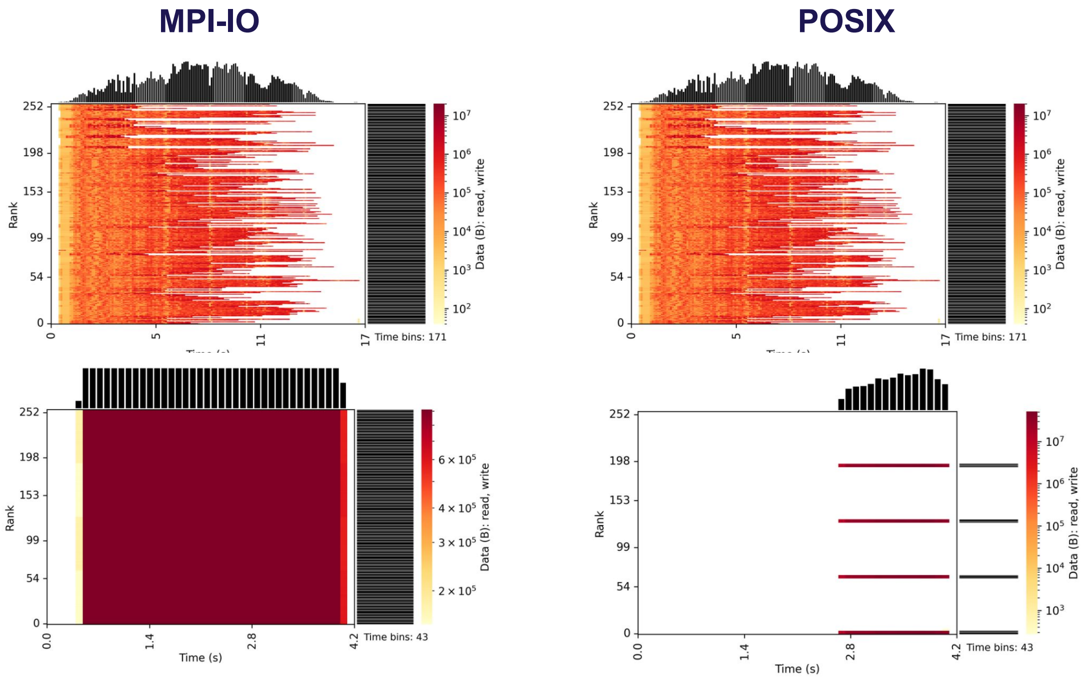
Access Size	Count
1048576	8191
96	2
2048	1
1046528	1

Collective I/O yields 26x improvement over no chunking, and 9x improvement over chunking!!!

Hands on exercises:
https://github.com/radix-io/hands-on

Tuning high-level (HDF5) data access

Optimizing application interactions with the I/O stack



Darshan I/O activity heatmaps illustrate how different the I/O behavior is for the unoptimized independent configuration (**top**) and the most performant collective I/O configuration (**bottom**).

Hands on exercises: https://github.com/radix-io/hands-on

Summarizing I/O tuning options

As a user of I/O interface X, what tuning vectors do I have?

I/O Interface	Striping	Alignment	Collective I/O	Chunking
HDF5	✓	✓	✓	✓
PnetCDF	✓	✓	✓	X
MPI-IO	✓	✓	✓	X
POSIX	✓	✓ -	X	X

Hands on exercises:
https://github.com/radix-io/hands-on

Summarizing I/O tuning options

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MPI-IO	✓	✓	✓	X
POSIX	✓	✓ -	X	X

Automatically align application data and library metadata, if user requests so.

Collective I/O can be automatically aligned.

POSIX I/O requires manually aligning every access.

Hands on exercises:
https://github.com/radix-io/hands-on

Summarizing I/O tuning options

As a user of I/O interface X, what tuning vectors do I have?

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PnetCDF	✓	✓	✓	X
MPI-IO	✓	✓	✓	X
POSIX	✓	✓ -	X	X

Just another reminder that high-level I/O libraries are here to make your life easier!

- I/O optimization strategies like collective I/O & chunking can net large performance gains, especially when combined with striping and alignment optimizations.

Additional Darshan tips and tricks

Finer-grained details with Darshan: DXT tracing

By default, Darshan captures a fixed set of counters for each file.

With DXT (Darshan Extended Tracing), Darshan additionally traces every read/write operation (for POSIX and MPI-IO interfaces).

Enabled by setting **DXT_ENABLE_IO_TRACE** env variable.

Finer grained instrumentation data comes at a cost of additional overhead and larger logs.

```
export DXT_ENABLE_IO_TRACE=1

mpiexec -n 256 --ppn 64 ./helloworld
```


Hands on exercises:
https://github.com/radix-io/hands-on

Finer-grained details with Darshan: DXT tracing

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```
# DXT, file_id: 1163774110118722858, file_name: /grand/projects/ATPESC2023/usr/snyder/hello
# DXT, rank: 0, hostname: x3202c0s1b0n0
# DXT, write_count: 160, read_count: 0
# DXT, mnt_pt: /, fs_type: overlay
# Module    Rank  Wt/Rd  Segment          Offset       Length    Start(s)      End(s)
 X_POSIX       0  write        0               0      1048576      3.9347      3.9468
 X_POSIX       0  write        1       167772160      1048576      4.2503      4.2575
 X_POSIX       0  write        2       335544320      1048576      4.5495      4.5564
 X_POSIX       0  write        3       503316480      1048576      4.8632      4.8707
```

Trace includes the timestamp, file offset, and size of every I/O operation on every rank. `darshan-dxt-parser` utility can provide a raw text dump of the trace.

Hands on exercises: https://github.com/radix-io/hands-on

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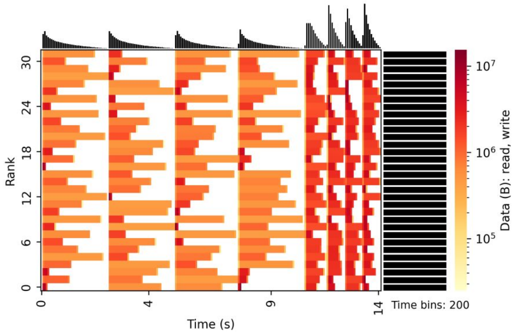

Traces can be visualized using job summary report heatmaps or custom analysis tools.

Hands on exercises: https://github.com/radix-io/hands-on

Darshan runtime library configuration

To bound memory overheads, Darshan imposes several internal memory limits (total memory usage, per-module record limits, etc.).

For some workloads, default limits may be exceeded resulting in partial instrumentation data.

To offer user's more control over memory limits and instrumentation scope, Darshan provides a comprehensive runtime configuration system.

- Environment variables or config files

```
#    KEY                  VALUE                  MODULES
NAME_EXCLUDE          ^/home                       *
NAME_EXCLUDE          .pyc$                        *
NAME_EXCLUDE          .so$                         *
NAME_INCLUDE          .h5$                         *

MODMEM      8

MAX_RECORDS           4000                       POSIX

MOD_ENABLE            DXT_POSIX,DXT_MPIIO

APP_EXCLUDE           git,ls,sed
```

Regular expressions can be specified to control whether matching record name patterns are included/excluded in Darshan instrumentation.

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MODMEM      8

MAX_RECORDS         4000                    POSIX

MOD_ENABLE          DXT_POSIX,DXT_MPIIO

APP_EXCLUDE         git,ls,sed
```

Settings are also offered to control total per-process memory usage (8 MiB) and per-module maximum record counts (4000 POSIX records).

Hands on exercises: https://github.com/radix-io/hands-on

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NAME_INCLUDE        .h5$                    *

MODMEM      8

MAX_RECORDS         4000                    POSIX

MOD_ENABLE          DXT_POSIX,DXT_MPIIO

APP_EXCLUDE         git,ls,sed
```

Additional settings allow control over enabled/disabled modules, as well as application names that should be included/excluded from instrumentation.

A changing HPC data management landscape

A changing HPC data management landscape

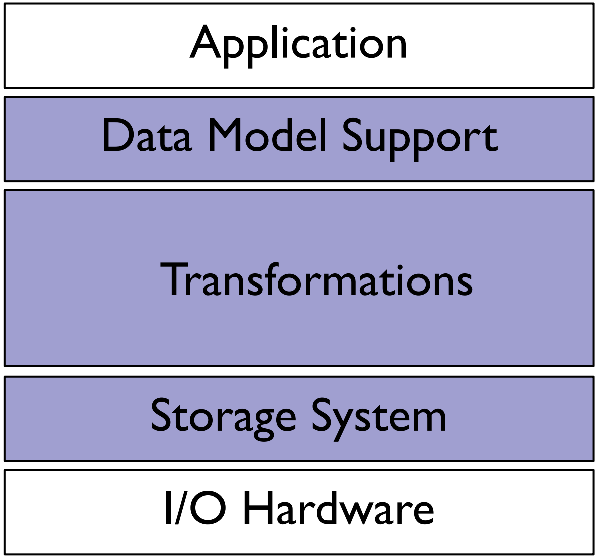
The various technologies covered today form much of the foundation of the traditional HPC data management stack.

- Variations on this stack have been deployed at HPC facilities and leveraged by users for high-performance parallel I/O for decades.

But, the HPC computing landscape is changing, even if slowly.

Changes are being driven at both ends of the stack.

- Newly embraced compute paradigms
- Emerging storage technologies



Emerging storage technologies

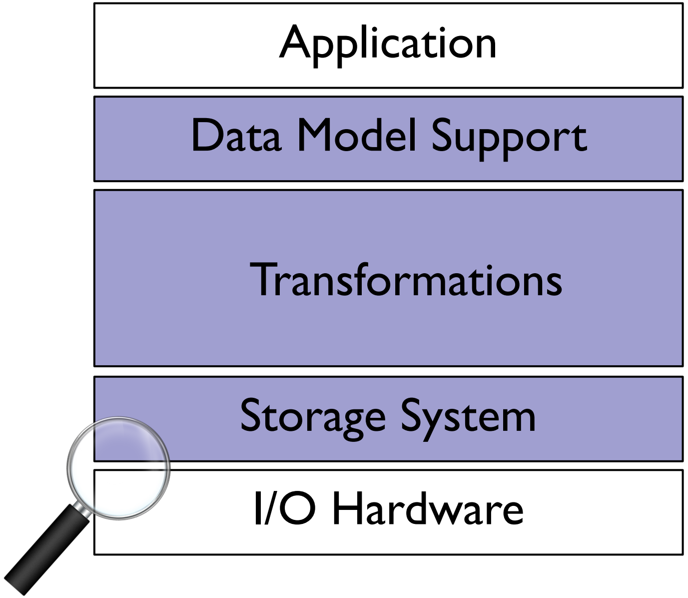
HPC storage technology is changing to meet the diverse I/O needs of scientific applications.

Traditionally, HPC users have had limited storage options for scientific data:

- One-size-fits-all parallel file systems, typically deployed over large arrays of hard disk drives

Growing application I/O demands and evolving hardware trends are leading the way to exciting new HPC storage:

- Storage systems based on high-performance flash devices and emerging storage class memory (SCM) devices
- New storage services offering appealing alternatives to traditional parallel file systems



Hands on exercises:
https://github.com/radix-io/hands-on

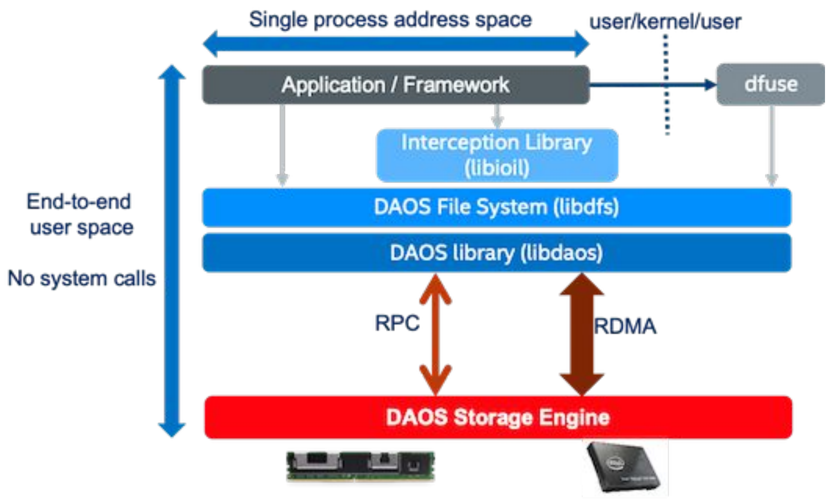
Emerging storage technologies: DAOS

ALCF Aurora features Intel's DAOS storage system, a first-of-a-kind object-based storage system for large-scale HPC platforms.

- Leverages both SCM and SSDs for storage

DAOS offers multiple I/O interfaces to users:

- Filesystem emulation API allowing legacy POSIX file access to DAOS storage
- Native object-based APIs (e.g.., key-val, array) offering more powerful semantics compared to POSIX-like file APIs
  - Data locality, replication strategy, etc.



Various access methods for DAOS users.

Figure courtesy of Intel

Hands on exercises: https://github.com/radix-io/hands-on

Emerging storage technologies: DAOS

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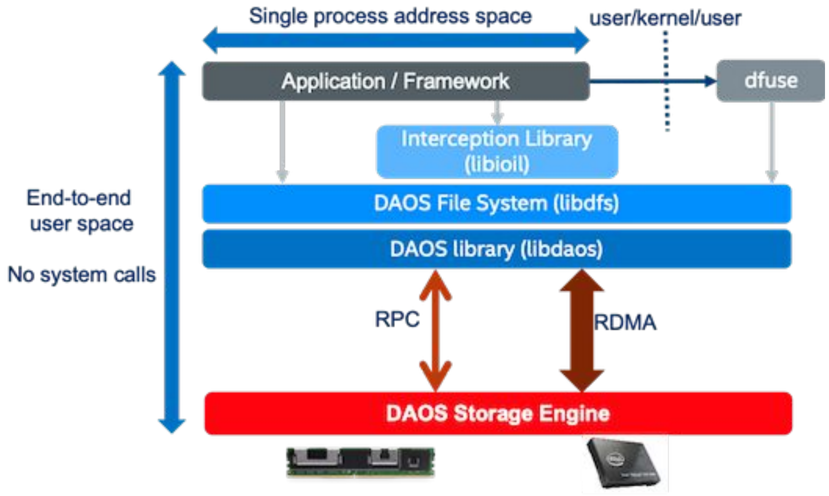
- Leverages both SCM and SSDs for storage

DAOS offers multiple I/O interfaces to users:

> Perhaps most key to the I/O performance of DAOS is that the libraries are all *userspace*, allowing bypass of costly calls into the kernel for handling of I/O as with POSIX.



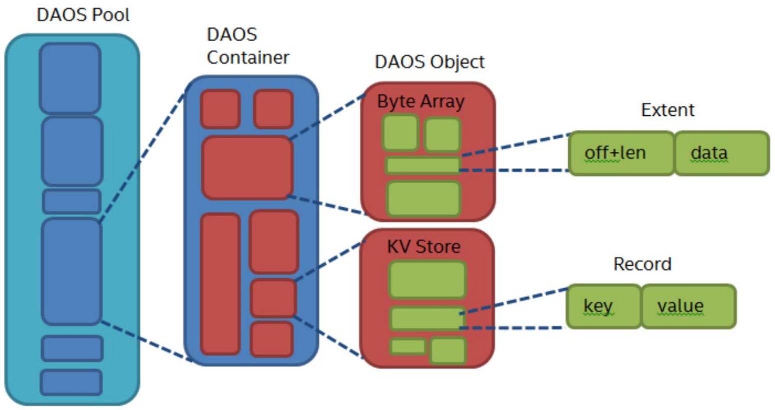
Various access methods for DAOS users.

Figure courtesy of Intel

Emerging storage technologies: DAOS

DAOS's native object interfaces allow for constructing powerful and performant data storage models not shackled by POSIX semantics.

- Array objects
  - Extent-based access, similar to files
- Key-val objects
  - Data accessed using arbitrary keys
  - Keys are split into a dkey (distribution key) and an akey (attribute key) to offer users control over data locality
    - All keys with same dkey are co-located on the same DAOS storage target



DAOS storage model. DAOS objects can be accessed using either key-val or array interfaces.

Figure courtesy of Intel

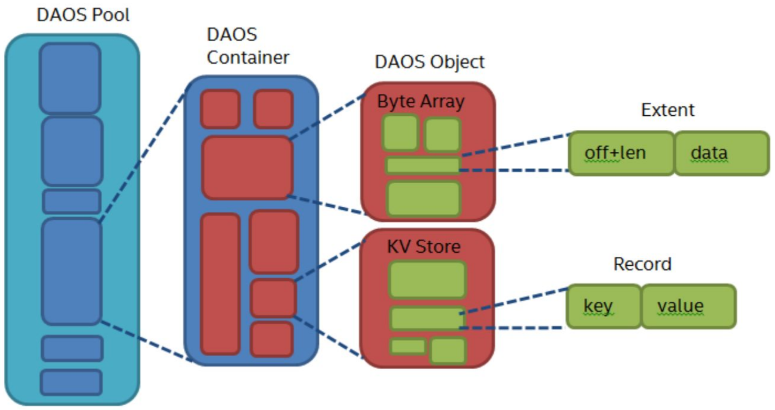
Hands on exercises: https://github.com/radix-io/hands-on

Emerging storage technologies: DAOS

DAOS's native object interfaces allow for constructing powerful and performant data storage models not shackled by POSIX semantics.

The traditional components of the HPC I/O stack that we have learned about today (e.g., MPI-IO and HDF5) have been modified to allow mapping of their storage models onto DAOS objects to get the best performance.

Development of Darshan instrumentation modules for DAOS APIs is well underway and should be included in our next release.



DAOS storage model. DAOS objects can be accessed using either key-val or array interfaces.

Figure courtesy of Intel

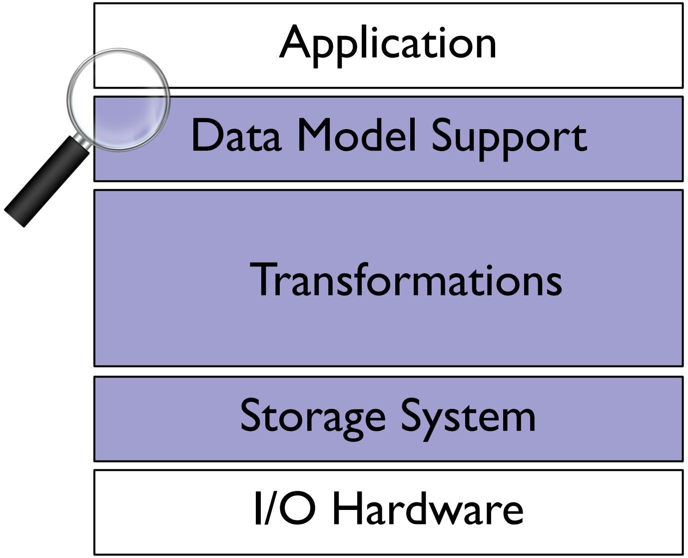
New scientific computing paradigms

Understanding and improving I/O behavior in novel HPC applications and compute frameworks is critical to scientific productivity.

Large-scale MPI applications are still the norm at most HPC centers, but other non-MPI compute frameworks are gaining traction:

- AI/ML (TensorFlow, Keras, PyTorch, Ray)
- Data analytics frameworks (Dask, PySpark)
- Other non-MPI distributed computing frameworks (Legion, UPC)

Many of these frameworks define their own data models, have their own mechanisms for managing distributed tasks, and demonstrate unique I/O access patterns.



Darshan instrumentation beyond MPI

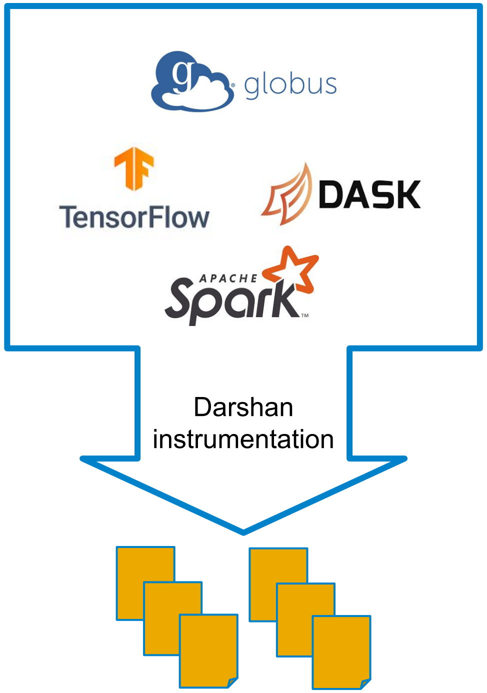
Though originally designed for MPI apps, Darshan was re-designed to support instrumentation in non-MPI contexts as well:

- Uses GCC-specific library constructor/destructor attributes to initialize/shutdown the Darshan library (instead of `MPI_Init`/`MPI_Finalize`)

To enable non-MPI mode, users must explicitly opt-in by setting the **`DARSHAN_ENABLE_NONMPI`** environment variable.

- A unique log will be generated for every process that executes.
- Often best to limit instrumentation scope to the target executable:

```
LD_PRELOAD=/path/to/libdarshan.so \
DARSHAN_ENABLE_NONMPI=1 \
./exe <args>
```



Caveats for instrumenting Python with Darshan

Recent Darshan development efforts have focused on enabling comprehensive instrumentation of a growing Python software ecosystem in HPC:

1. Started with Darshan's support for non-MPI, as Python often uses other mechanisms for parallelizing/distributing work across multiple processes

```
LD_PRELOAD=/path/to/libdarshan.so \
DARSHAN_ENABLE_NONMPI=1 \
python script.py <script_args>
```


Hands on exercises:
https://github.com/radix-io/hands-on

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Recent Darshan development efforts have focused on enabling comprehensive instrumentation of a growing Python software ecosystem in HPC:

1. Started with Darshan's support for non-MPI, as Python often uses other mechanisms for parallelizing/distributing work across multiple processes
2. Darshan library configuration support for focusing scope of Darshan instrumentation

```
# exclude Python compiled code, shared libraries, etc.
NAME_EXCLUDE    \.pyc$, \.so$,    *

# pre-allocate 5000 POSIX records (default 1024)
MAX_RECORDS     5000      POSIX

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

Otherwise, Darshan exhausts its memory and only instruments a portion of the application I/O workload.

Caveats for instrumenting Python with Darshan

Recent Darshan development efforts have focused on enabling comprehensive instrumentation of a growing Python software ecosystem in HPC:

1. Started with Darshan's support for non-MPI, as Python often uses other mechanisms for parallelizing/distributing work across multiple processes
2. Darshan library configuration support for focusing scope of Darshan instrumentation
3. Enhancements to Darshan to handle Pythonic approaches to spawning/terminating new processes
   - Support for restarting the Darshan library on `fork()` child processes
   - Graceful handling of Python approaches for terminating new processes
     - Child processes frequently use `_exit()` or are issued `SIGTERM` signals from the parent process, sidestepping Darshan's typical shutdown procedure.

Caveats for instrumenting Python with Darshan

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2. Darshan library configuration support for focusing scope of Darshan instrumentation
3. Enhancements to Darshan to handle Pythonic approaches to spawning/terminating new processes

We recommend building Darshan with the "**`--enable-mmap-logs`**" option to help protect against this. This setting will enable capture of uncompressed Darshan logs in `/tmp` for processes that terminate abruptly. These logs can be compressed and moved somewhere longer term with the following command:

```
darshan-convert /tmp/log.darshan /path/to/logs/log.darshan
```

Other I/O analysis tools

Darshan-based analysis tools

Using Darshan as a starting point for developing new I/O analysis tools is attractive for a couple of reasons:

1. Darshan is commonly deployed in production at many HPC sites, making its I/O characterization data generally accessible to custom tools.
2. Recent PyDarshan work has enabled much more agile development of Darshan-based I/O analysis tools in Python.

> We will start by considering a couple of Darshan-based I/O analysis tools: **DXT Explorer** and **Drishti.**

Hands on exercises:
https://github.com/radix-io/hands-on

DXT Explorer

- Darshan does not offer much in terms of DXT trace analysis tools beyond general I/O activity heatmaps.
- **DXT Explorer★** is an interactive web-based trace analysis tool for DXT data that was developed to provide:
  - Combined views of MPI-IO and POSIX activity
  - Zoom in/out capabilities to focus on subsets of ranks or specific time slices
  - Contextual information about I/O calls
  - Views based on operation type, size, and spatiality
- Interactive trace analysis with DXT Explorer can enable interesting new insights into app I/O behavior.

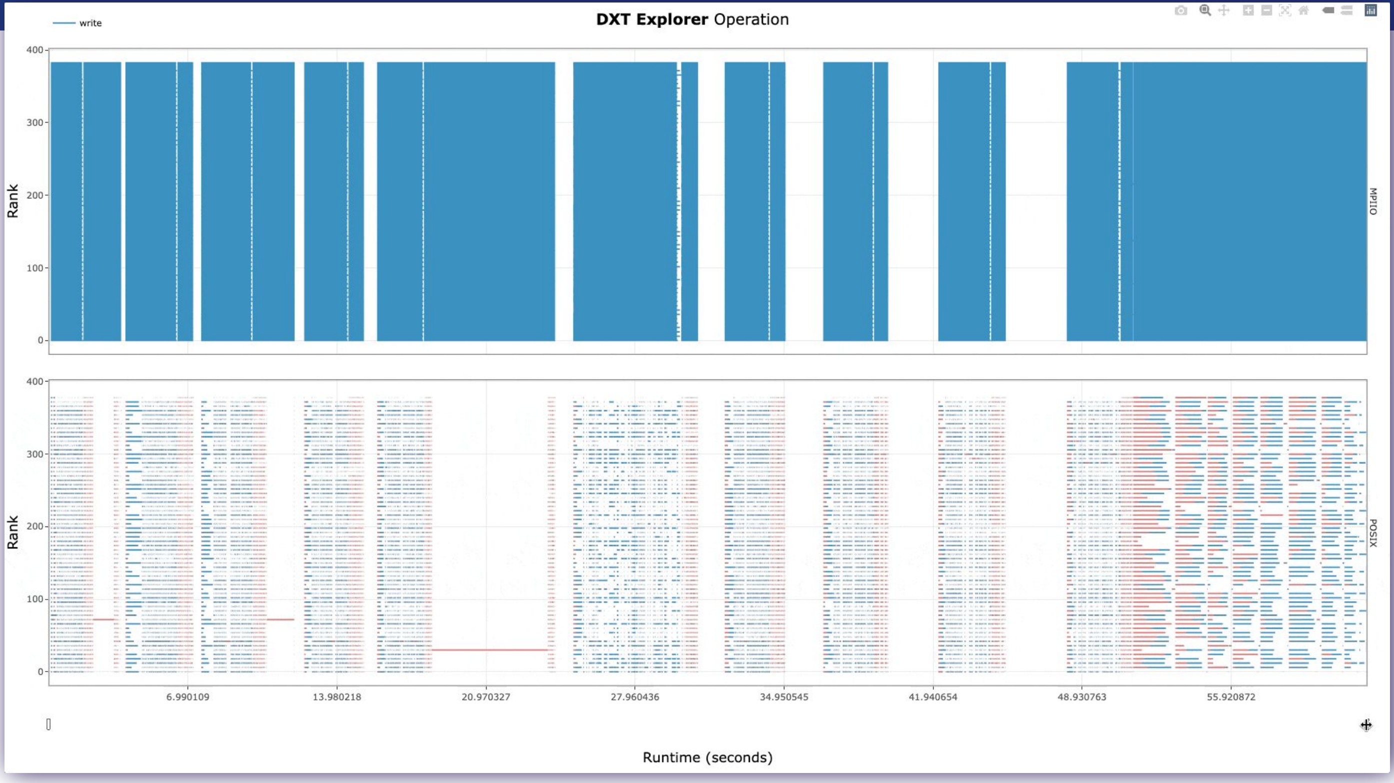
github.com/hpc-io/dxt-explorer

docker pull hpcio/dxt-explorer

★ DXT Explorer was developed by Jean Luca Bez (LBL). Slide content also provided courtesy of Jean Luca.

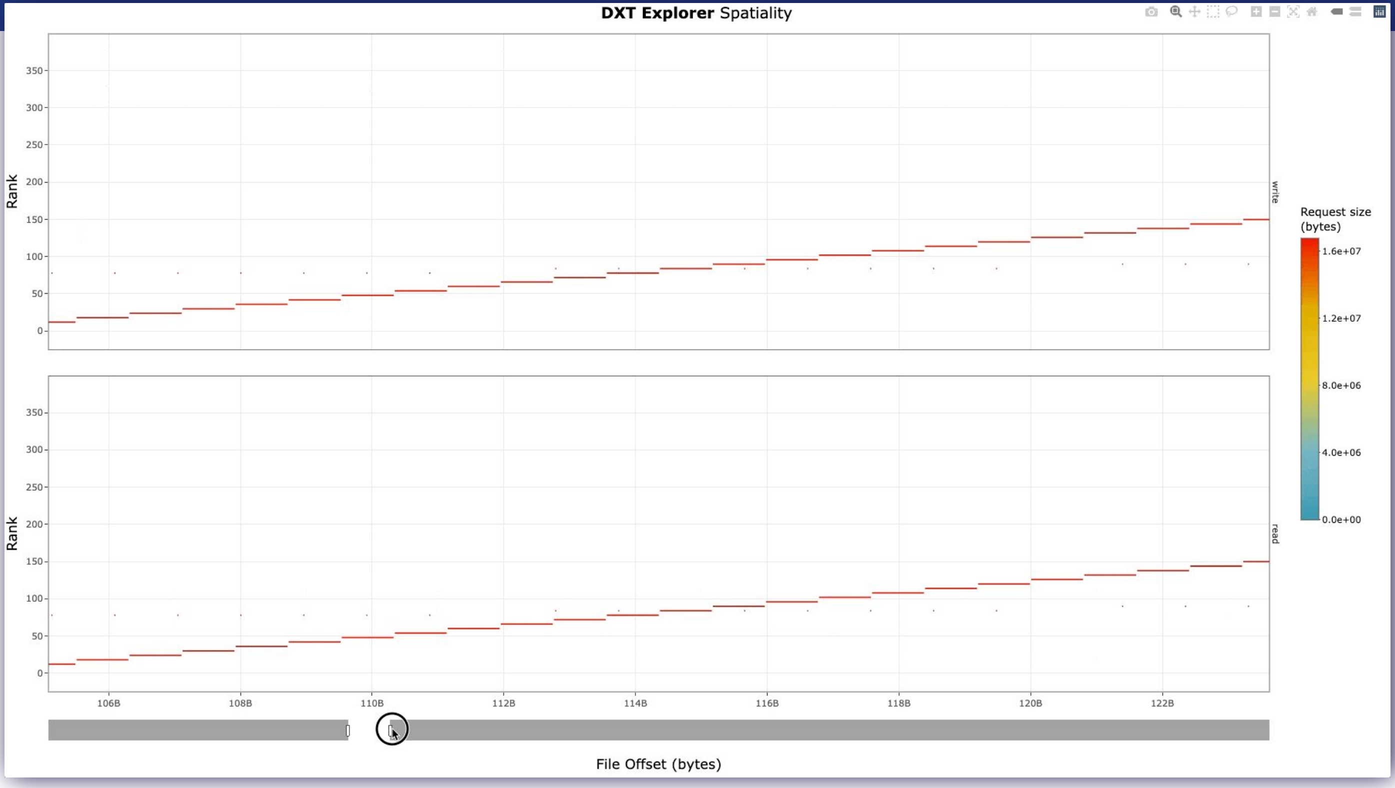
Bez, Jean Luca, et al. "I/O bottleneck detection and tuning: connecting the dots using interactive log analysis." *2021 IEEE/ACM Sixth International Parallel Data Systems Workshop (PDSW)*. IEEE, 2021.

DXT Explorer



Explore the timeline by zooming in and out and observing how the MPI-IO calls are translated to the POSIX layer. For instance, you can use this feature to detect stragglers.

DXT Explorer



Explore the spatiality of accesses in file by each rank with contextual information. Understand how each rank is accessing each file.

Hands on exercises: https://github.com/radix-io/hands-on

Drishti

- Darshan can capture detailed I/O characterization data for an app, but translating this raw data to actionable tuning feedback is a significant challenge.
- **Drishti★** is a command-line tool to guide end-users in optimizing I/O in their applications by detecting typical I/O performance pitfalls and providing a set of recommendations.
- Drishti checks each given Darshan log against 30+ heuristic triggers for various I/O issues and suggests actions to take to resolve them.
  - 4 levels of triggers: *high, warning, ok, info*

github.com/hpc-io/drishti-io

docker pull hpcio/drishti

★ Drishti was developed by Jean Luca Bez (LBL). Slide content also provided courtesy of Jean Luca.

Bez, Jean Luca, Hammad Ather, and Suren Byna. "Drishti: guiding end-users in the I/O optimization journey." 2022 IEEE/ACM International Parallel Data Systems Workshop (PDSW). IEEE, 2022.

Hands on exercises:
https://github.com/radix-io/hands-on

Drishti

```
Drishti

DRISHTI v.0.3

 JOB:            1190243
 EXECUTABLE:     bin/8_benchmark_parallel
 DARSHAN:        jlbez_8_benchmark_parallel_id1190243_7-23-45631-11755726114084236527_1.darshan
 EXECUTION DATE: 2021-07-23 16:40:31+00:00 to 2021-07-23 16:40:32+00:00 (0.00 hours)
 FILES:          6 files (1 use STDIO, 2 use POSIX, 1 use MPI-IO)
 PROCESSES       64
 HINTS:          romio_no_indep_rw=true cb_nodes=4

 1 critical issues, 5 warnings, and 5 recommendations

METADATA

 ▶ Application is read operation intensive (6.34% writes vs. 93.66% reads)
 ▶ Application might have redundant read traffic (more data was read than the highest read offset)
 ▶ Application might have redundant write traffic (more data was written than the highest write offset)

OPERATIONS

 ▶ Application issues a high number (285) of small read requests (i.e., < 1MB) which represents 37.11% of all
read/write requests
   ↪ 284 (36.98%) small read requests are to "benchmark.h5"
   ↪ Recommendations:
     ↪ Consider buffering read operations into larger more contiguous ones
     ↪ Since the appplication already uses MPI-IO, consider using collective I/O calls (e.g. MPI_File_read_all() or
MPI_File_read_at_all()) to aggregate requests into larger ones
```

Overall information about the Darshan log and execution

Number of critical issues, warning, and recommendations

Details on metadata and data operations

Critical issue and corresponding recommendation for `benchmark.h5`

Other I/O analysis tools

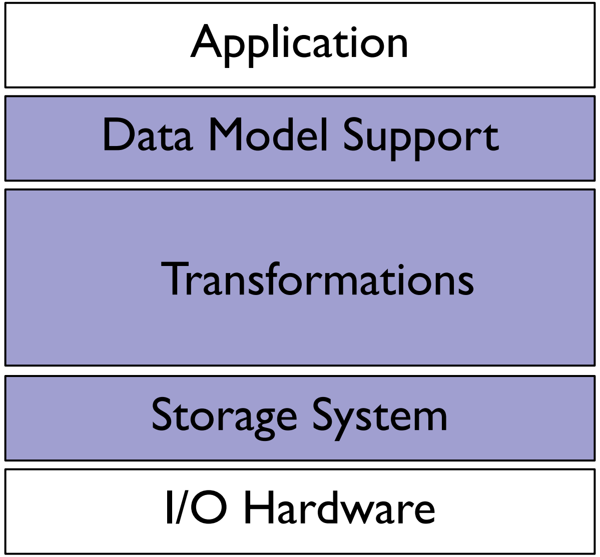
- There are some other notable tools that may be of use for gaining more insights into the I/O behavior of an application:
  - **Recorder**: https://github.com/uiuc-hpc/Recorder
    - Multi-level detailed I/O traces and corresponding trace viz tools
    - More detail than DXT but not as production hardened
  - **DFTracer**: https://github.com/hariharan-devarajan/dftracer
    - Hybrid profiling tool capturing low-level I/O details (i.e., POSIX) as well as application-level profiling
    - Allows correlation of applications and frameworks (e.g., AI/ML frameworks) behavior with low-level I/O

Other I/O analysis tools

- There are some other notable tools that may be of use for gaining more insights into the I/O behavior of an application:
  - **TAU**: http://www.cs.uoregon.edu/research/tau/
    - General call profiling/tracing toolkit for HPC applications, including I/O routines
    - Tools for visualizing profiles/traces and detecting bottlenecks, etc.
    - See: https://hps.vi4io.org/_media/events/2019/sc19-analyzing-tau.pdf
  - **LDMS**: https://hmdsa.github.io/hmdsa/pages/tools/ldms
    - Beyond the application, includes detailed system metrics collection
    - Not typically something users deploy, but may be another resource to consider at some facilities

Wrapping up

- Hopefully this material proves useful in providing a deeper understanding of the different layers of the HPC I/O stack covered today, as well as potential tuning vectors available to you as user.
- **Some key takeaways:**
  - Optimizing your I/O workload can be challenging, but can offer large performance gains.
  - Use high-level I/O libraries where you can.
  - Don’t always count on I/O libraries or file systems to automatically provide you the best performance out-of-the-box.



Wrapping up

- Darshan is an invaluable tool for understanding application I/O behavior and informing tuning efforts – use it to instrument application workloads, analyze resulting performance, and experiment with different I/O strategies!
- Please reach out with questions, feedback, etc.

DARSHAN **https://www.mcs.anl.gov/research/projects/darshan/**

github.com/darshan-hpc/darshan

darshan-io.slack.com

Application

Data Model Support

Transformations

Storage System

I/O Hardware

Hands on exercises:
https://github.com/radix-io/hands-on

Thank you!