Accelerating HDF5's Parallel I/O for Exascale using DAOS

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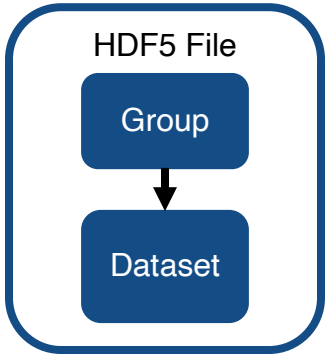
Outline

- **What's new in this presentation**
  - Full paper: "Accelerating HDF5 I/O for Exascale using DAOS," in IEEE Transactions on Parallel and Distributed Systems, doi: 10.1109/TPDS.2021.3097884.
- **HDF5 Parallel I/O w/Native File Format**
- **Introduction to Intel ® DAOS**
- **HDF5 DAOS VOL Connector and File Format**
- **New Features**
- **Evaluation and Application Example**
- **Conclusion**

HDF5 Parallel I/O w/Native File Format

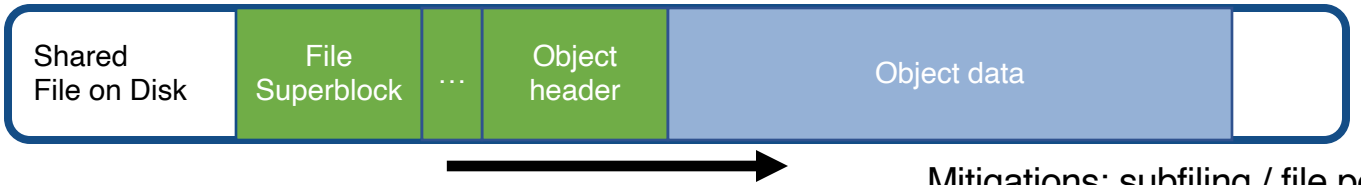
- 


```
H5Pset_fapl_mpio()
H5Fcreate()
H5Gcreate()
H5Dcreate()
H5Dwrite()
H5Dread()
```

Collective metadata operations
(not an API or data model restriction)

Collective or Independent raw data operations

- **POSIX I/O was designed for disk-based storage**
  - High-latency to write data at random offsets because of mechanical aspects
  - Current native HDF5 file format inherited POSIX I/O block-based model (serial)

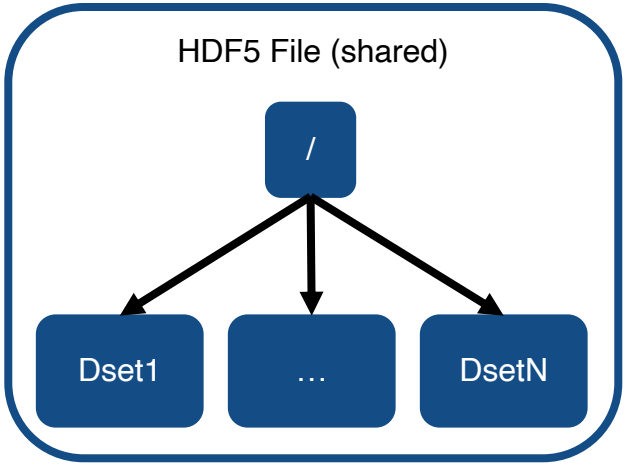


Mitigations: subfiling / file per process I/O
Added complexity, always limited by POSIX
Object-based model of HDF5 lost in storage

HDF5 Parallel I/O w/Native File Format

- **In Theory**

```
sprintf(dset_name, “Dset%d”, my_rank + 1);
fapl = H5Pset_fapl_mpio(…);
file = H5Fcreate(…);
dset = H5Dcreate(file, dset_name, …);
H5Dwrite(dset, …);
```

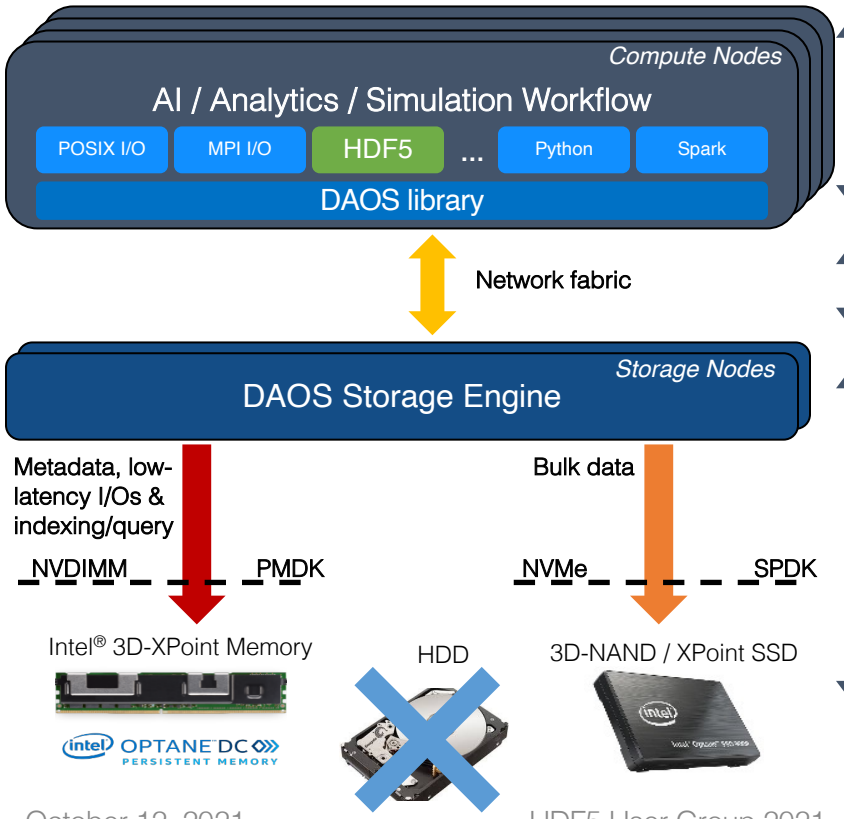


- **In Practice**

```
fapl = H5Pset_fapl_mpio(…);
file = H5Fcreate(…, fapl, …);
for (i = 0; i < n_ranks; i++) {
    sprintf(dset_name, “Dset%d”, i + 1);
    dset[i] = H5Dcreate(file, dset_name, …);
}
H5Dwrite(dset[my_rank], …);
```

Intel ® DAOS

Credit: Mohamad Chaarawi (Intel Corporation)



- DAOS library directly linked with the applications
- No need for dedicated cores
- Low memory/CPU footprint
- End-to-end OS bypass
- KV API, non-blocking, lockless, snapshot support

- Low-latency & high-message-rate communications
- Native support for RDMA & scalable collective operations
- Support for Infiniband, Slingshot, etc through OFI libfabric

- Fine-grained I/O with media selection strategy
- Only application data on SSD to maximize throughput
- Small I/Os aggregated in pmem & migrated to SSD in large chunks
- Full user space model with no system calls on I/O path
- Built-in storage management infrastructure (control plane)
- NFSv4-like ACL

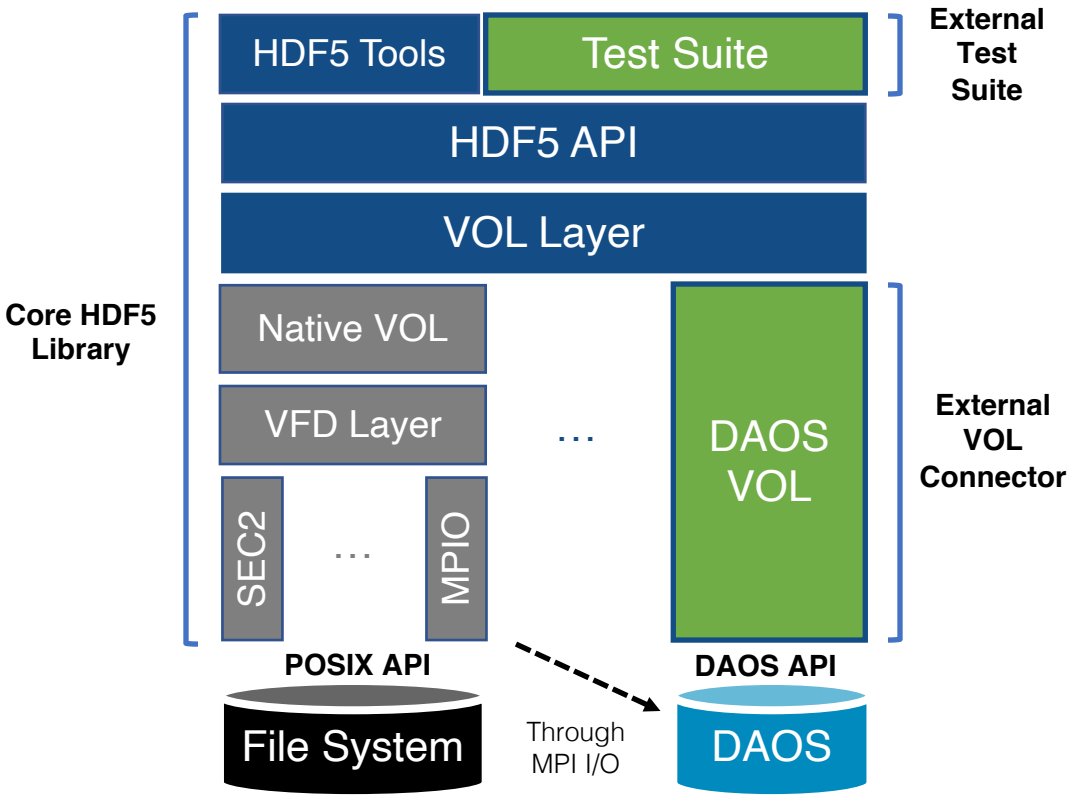
Delivers high-IOPs, high-bandwidth and low-latency storage with advanced features in a single tier

HDF5 VOL Architecture

- New Component
- Enhanced Component
- Native Component

- **Three main components:**
  - HDF5 Library
  - DAOS VOL Connector
  - (External) HDF5 Test Suite

- **Tools support:**
  - h5dump, h5ls, h5diff, h5repack, h5copy, etc



HDF5 DAOS VOL Connector

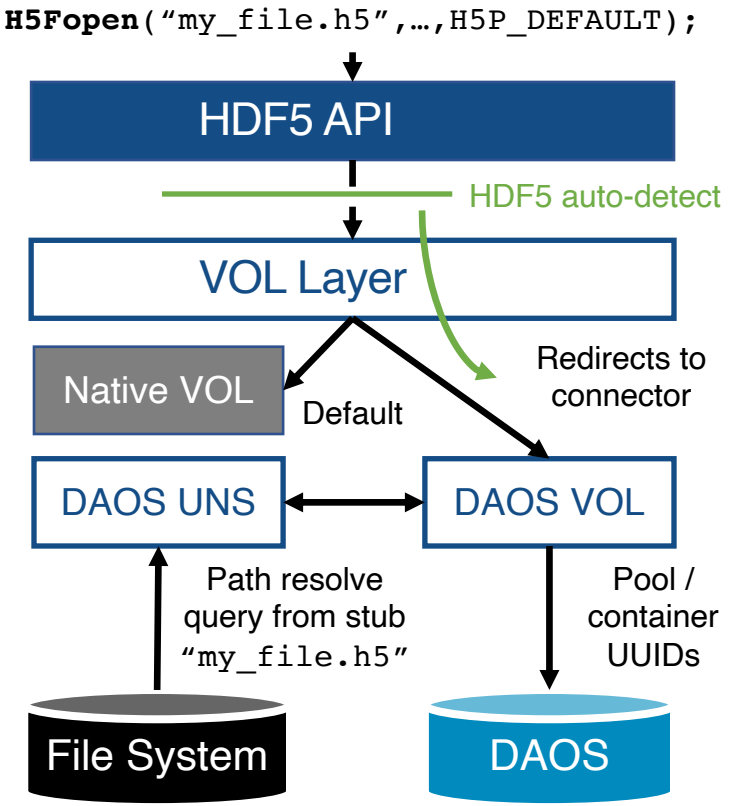
- **Allows the creation and use of HDF5 files in DAOS**
  - Minimal or no code changes for application developer (if only looking for compatibility)
  - Two ways to tell which connector to use
    - HDF5 file access property list (**recommended for new files or when manipulating multiple VOLs**)

```
herr_t H5Pset_fapl_daos(hid_t fapl_id,
const char *pool, const char *sys_name)
```

    - Environment variable

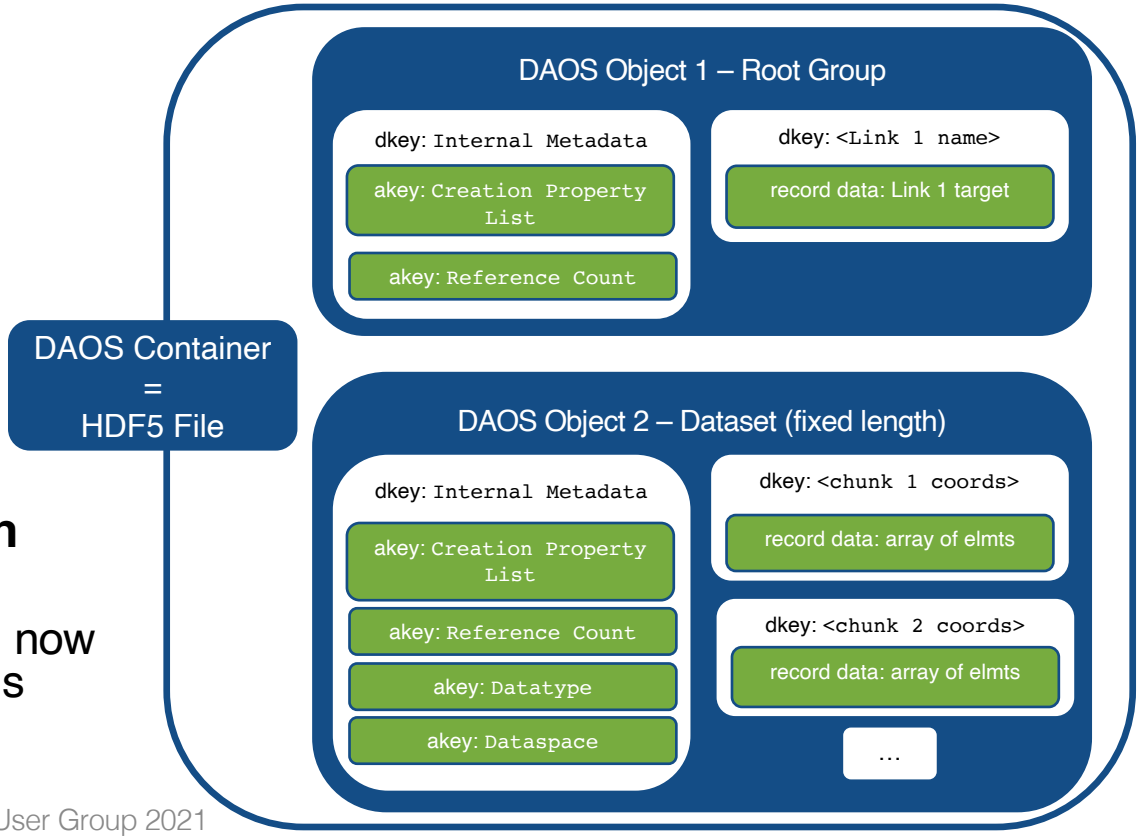
```
HDF5_VOL_CONNECTOR=daos
HDF5_PLUGIN_PATH=/path/to/connector/folder
```

  - **Auto-detect and Unified Namespace** component facilitates opening of DAOS files with the DAOS connector (embedded DAOS metadata through extended attributes)



HDF5 DAOS VOL "File" Format

- HDF5 File
  - Root Group
  - Dataset



- **Independent I/O through DAOS (K/V objects)**
  - Parallel I/O and chunking now become first-class citizens

Data control and Placement

- **Multiple options**
  - Chunking enabled by default for contiguous datasets, controlled with:

    `H5Pset_chunk()`
  - Set DAOS object class per DAOS object to control number of targets used for storing object (= **stripe count**):

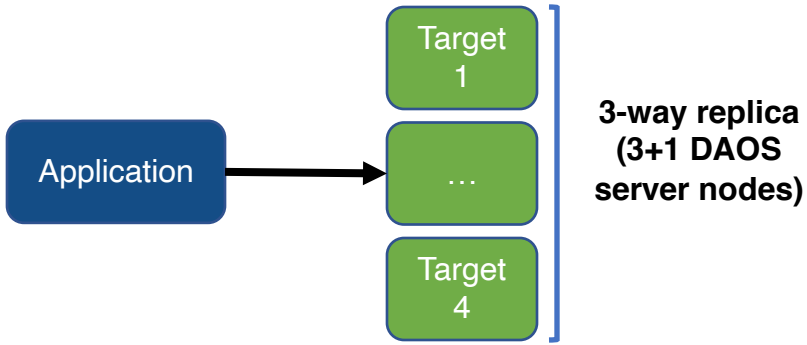
    `H5daos_set_object_class()`

    default uses all targets available
  - Set property to control numbers of **replicas** (for recovery), also controlled through:

    `H5daos_set_object_class()`

    default is no replica
  - Additional container properties (e.g. chksum, acl, rf) controlled with:

    `H5daos_set_prop()`



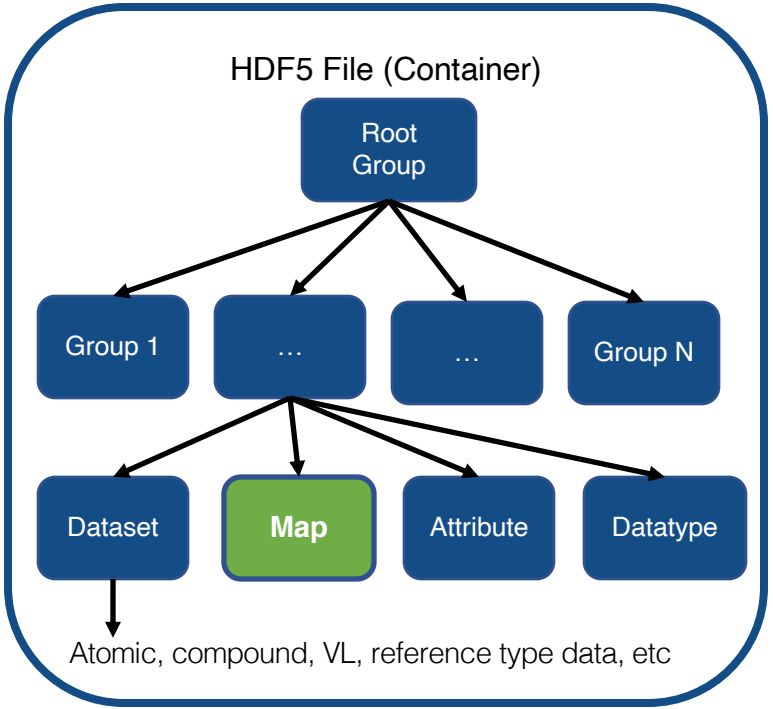
target ≠ storage node:
multiple storage targets per node

Features

- **All HDF5 features are currently supported except features specific to the native file format**
- **Additional features implemented**
  - Map objects (enabled by K/V objects)
  - File deletion
  - Independent metadata
    - HDF5 objects can be created independently
    - Currently enabled with:

```
H5daos_set_all_ind_metadata_ops()
```

    - **May become default behavior in the future**
  - Asynchronous I/O



Asynchronous I/O

- **Enables asynchrony using Event Set API**
  - Implemented at DAOS connector level
  - HDF5 API returns before operation completes, places operation in an “event set”, while tracking dependencies
    - Uses DAOS task engine

- **Asynchrony must be explicitly controlled by application**
  - Similar to existing async APIs, such as MPI non-blocking
  - Use async versions of all routines that may block
  - Beware of dependencies
    - e.g., **`H5Dcreate_async()`** → **`H5Dwrite_async()`** → **`H5Dclose_async()`**
    - **`H5ESwait()`** is responsible for advancing asynchronous operations

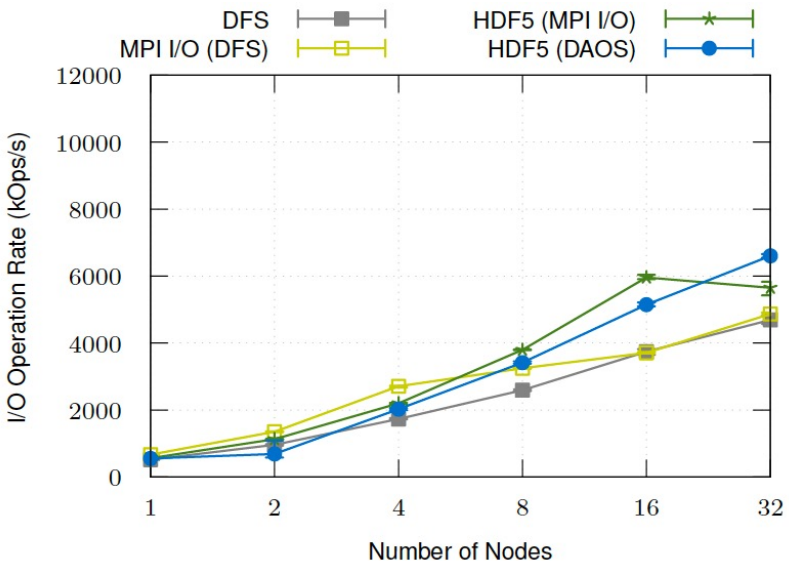
Evaluation – Configuration

- **DAOS system deployed on Frontera (TACC)**
  - 4 DAOS storage nodes
  - 24 Intel® Optane persistent memory DIMMs of 256GB each
  - InfiniBand HDR100 (100 Gb/s) connectivity to the compute nodes
  - Use only 28 cores within same NUMA node as InfiniBand card
  - 2 TB DAOS pool without NVMe backend to make exclusive use of persistent memory

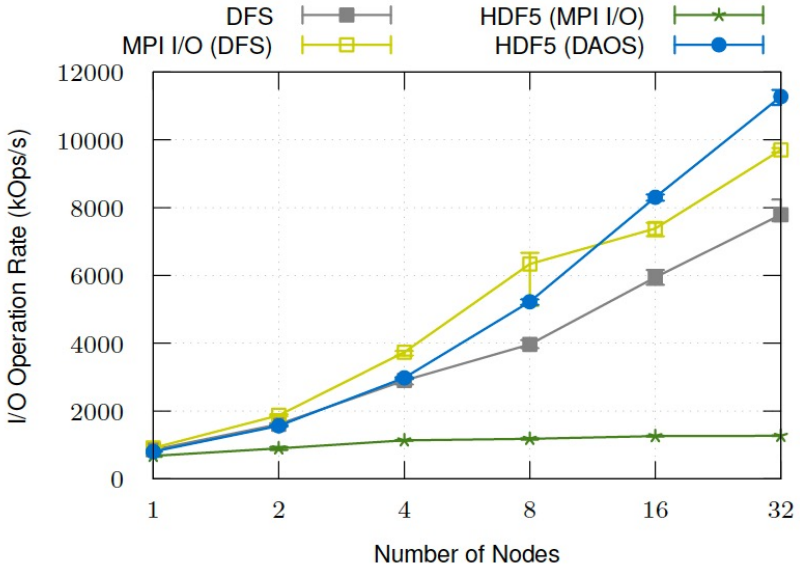
- **Software version used has evolved since then**
  - DAOS version used was 1.1.2.1
  - HDF5 version was 1.13.0rc5 and DAOS VOL version was 1.1.0rc3 (pre-release)

Evaluation – IOR small I/O (1 KB)

Write

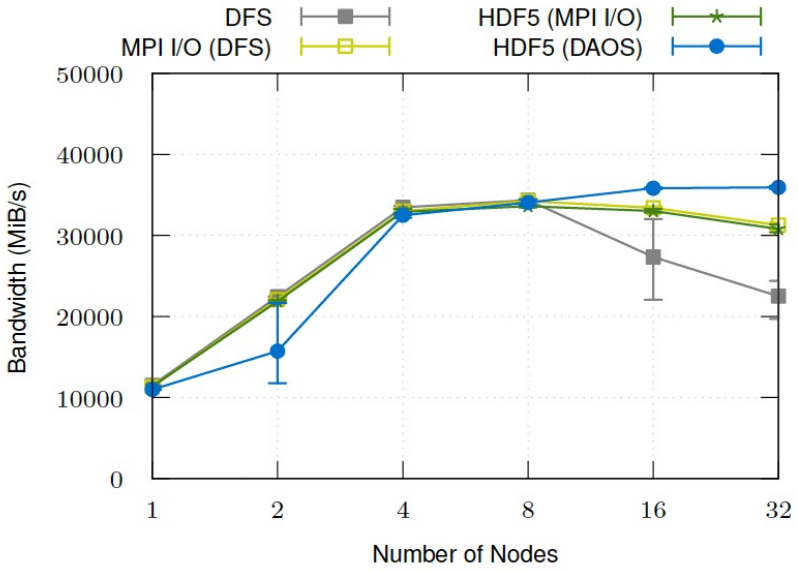


Read

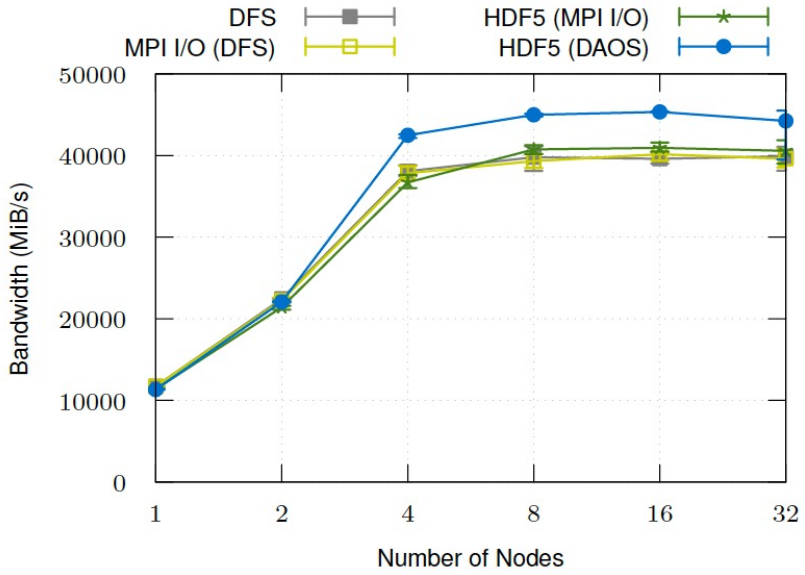


Evaluation - IOR large I/O (1 MB)

Write

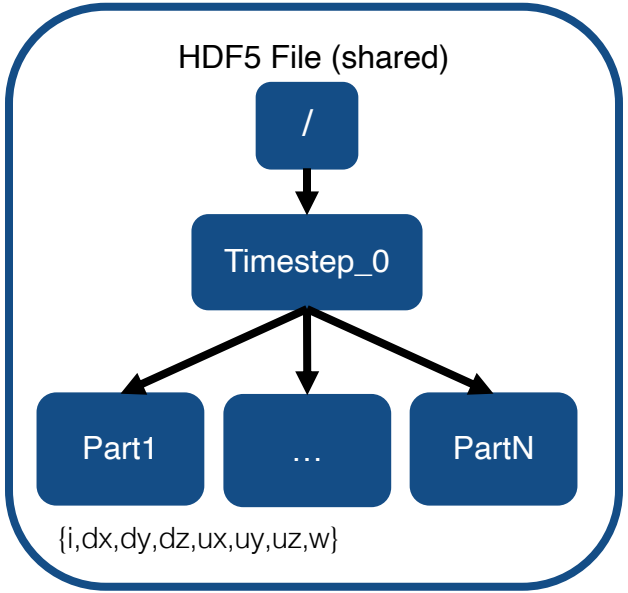


Read

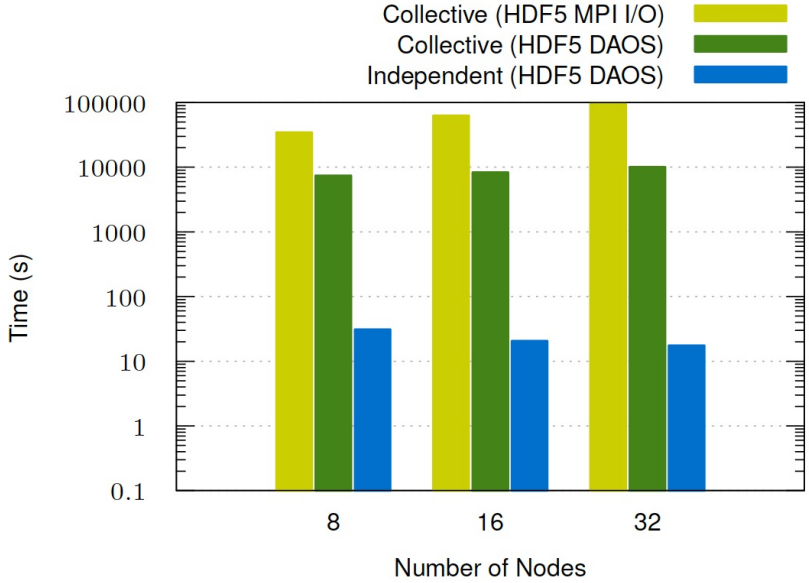


Evaluation – Example w/VPIC

Re-defined VPIC file structure for electron particle (N particles)



VPIC I/O performance using collective and independent group creation



Conclusion

- **Native file format inherited limitations from block-based model**
  - Switching to object-based model is more in line with HDF5 data model
  - New storage models can now be defined without any “parallel” constraints
    - Storage model should map application’s data model

- **Switching to DAOS VOL is a one-line code change**
  - However…
    - New features such as async I/O, maps, fine-grained data control and placement can only be fully utilized with DAOS
    - We expect application I/O kernels to be re-worked based on these new features
- **DAOS VOL reached release candidate status**
  - Will be fully released along with HDF5 1.13.0

Acknowledgments / Questions

- **DAOS VOL Connector repository:**
  - https://github.com/HDFGroup/vol-daos
- **More results / details in IEEE TPDS paper**
  - https://doi.org/10.1109/TPDS.2021.3097884

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