SCALABLE COMPUTING
SOFTWARE LABORATORY

ILLINOIS INSTITUTE
OF TECHNOLOGY

# Hermes

## A Multi-Tiered Distributed I/O Buffering System

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# Hermes Project

## The team

Collaborative project funded by NSF

NSF

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The HDF Group

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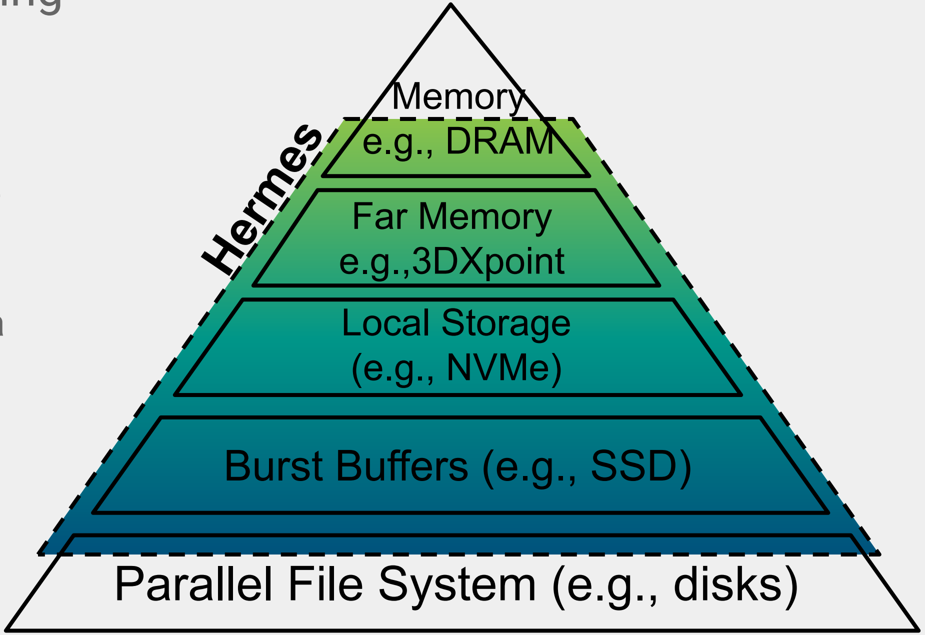
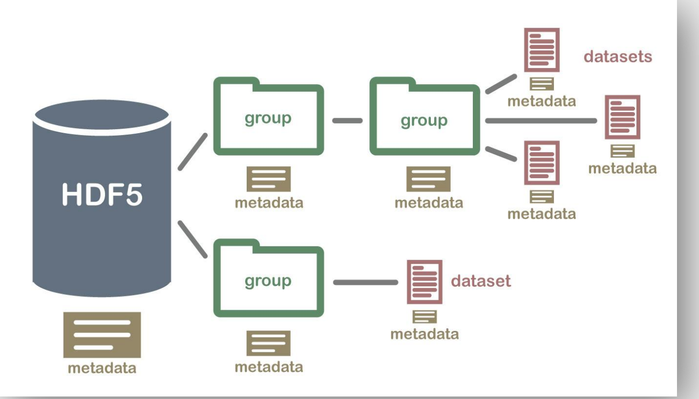
# Hermes Overview

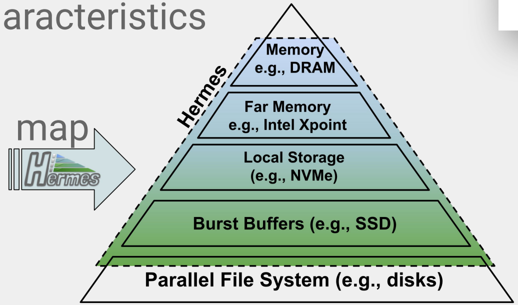
- A new, multi-tiered, distributed buffering system that:
  - Enables, manages, and supervises I/O operations in the Deep Memory & Storage Hierarchy (DMSH).
  - Offers selective and dynamic layered data placement.
  - Is modular, extensible, and performance-oriented.
  - Supports a wide variety of applications (scientific, BigData, etc.,).



# Hermes + HDF5

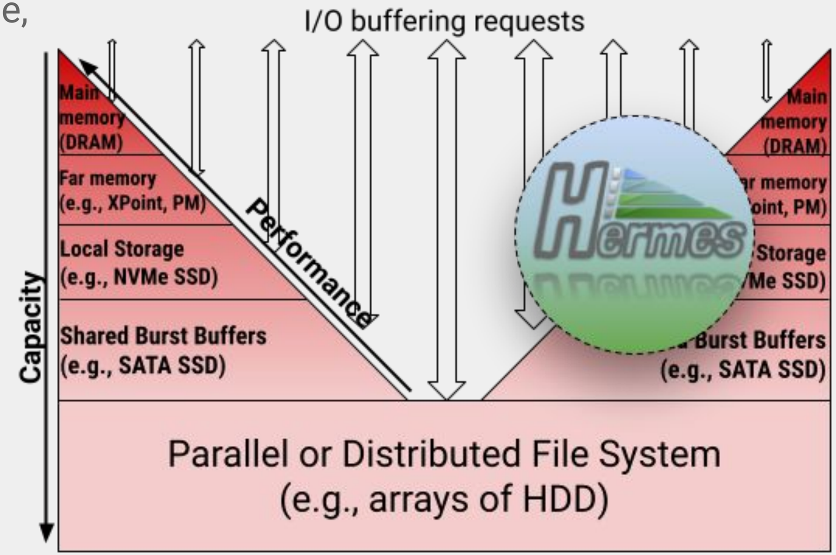
- HDF5 is a self-describing hierarchical data format which makes it ideal for Hermes
  - Utilize the rich metadata offered by HDF5 to efficiently place data in the hierarchy.
  - Leverage HDF5 characteristics
    - files,
    - groups,
    - datasets,
    - chunked I/O




map
Hermes
Hermes
Memory e.g., DRAM
Far Memory e.g., Intel Xpoint
Local Storage (e.g., NVMe)
Burst Buffers (e.g., SSD)
Parallel File System (e.g., disks)

# Objectives

- Hermes strives for:
  - being application- and system-aware,
  - maximizing productivity and path-to-science,
  - increasing resource utilization,
  - abstracting data movement,
  - maximizing performance, and
  - supporting a wide range of applications

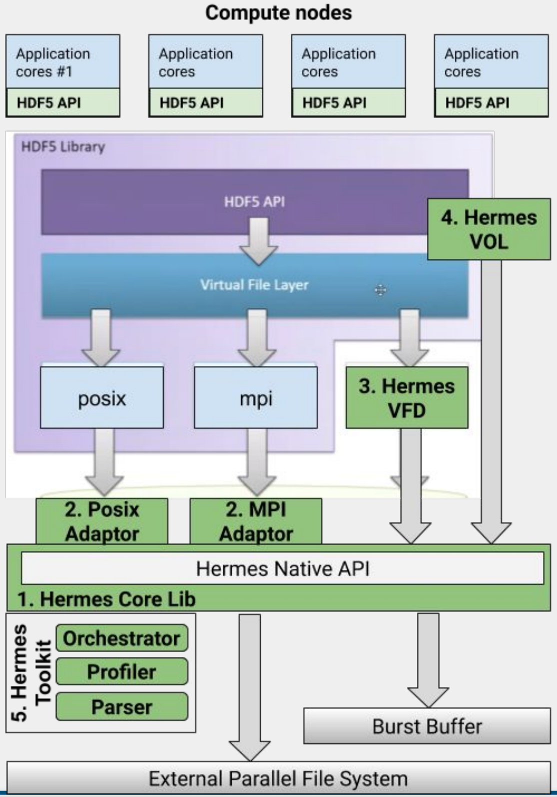

I/O buffering requests
Main memory (DRAM)
Far memory (e.g., XPoint, PM)
Local Storage (e.g., NVMe SSD)
Shared Burst Buffers (e.g., SATA SSD)
Performance
Capacity
Main memory (DRAM)
r memory oint, PM)
Storage Me SSD)
Burst Buffers (e.g., SATA SSD)
Hermes
Parallel or Distributed File System (e.g., arrays of HDD)

# Hermes

# Design and Architecture

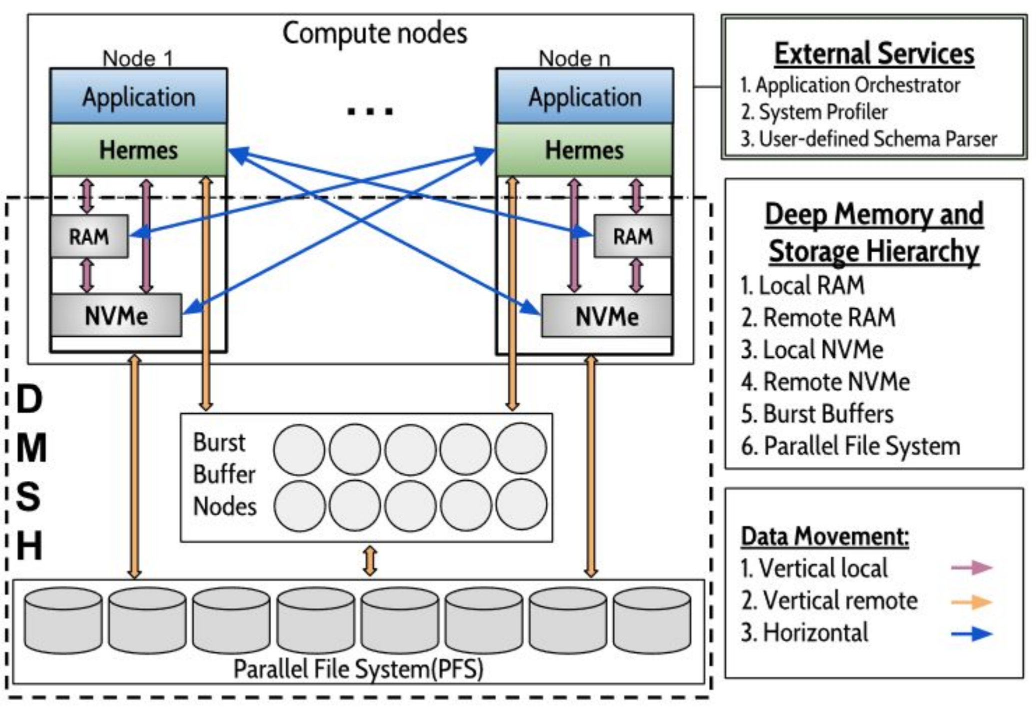
# Hermes Ecosystem

1. Hermes core library
   a. Manages tiers transparently
   b. Facilitates data movement in the hierarchy
   c. Provides native buffering API
2. Hermes Adapters
   a. POSIX, MPI-IO, Pub-Sub, etc
      i. Intercept I/O calls to Hermes
      ii. Boosts legacy app support
3. Hermes VFD
   a. Directs HDF5 I/O to Hermes native API
4. Hermes VOL
   a. Captures application's behavior and provides hints to Hermes core lib
5. Hermes Toolkit



# Hermes Architecture

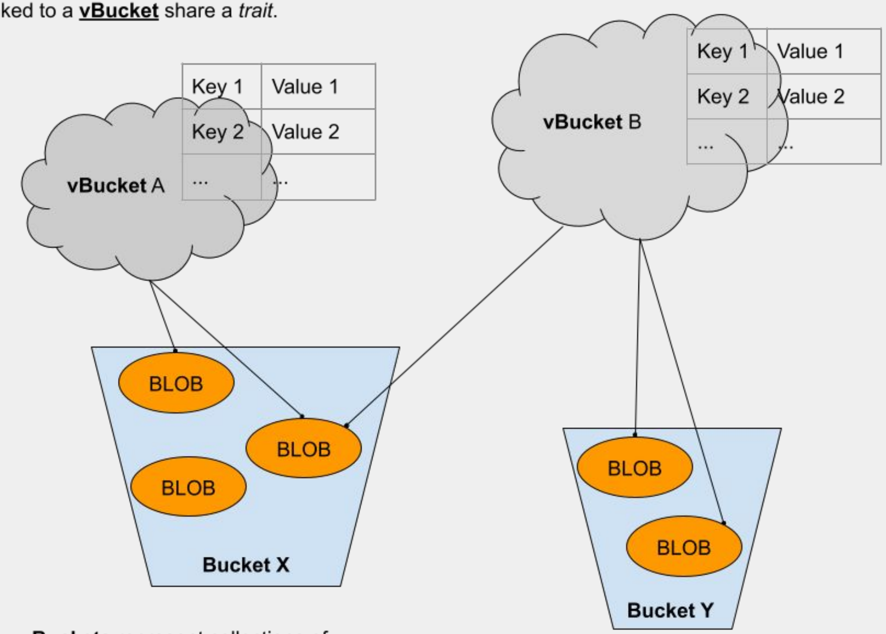
- Hermes machine model:
  - Large amount of RAM
  - Local NVMe and/or SSD device
  - Shared Burst Buffers
  - Remote disk-based PFS
- Hierarchy based on:
  - Access Latency
  - Data Throughput
  - Capacity
- Two data paths:
  - Vertical (within node)
  - Horizontal (across nodes)



# Hermes Data Model

- Blobs
  - Unit of data as key-value pairs
  - Value as uninterpreted byte arrays
  - Stored internally as a collection of buffers across multiple tiers
- Bucket
  - Collection of blobs
  - Flat blob organization
- Virtual Bucket
  - Linked blobs across buckets
  - Attached capabilities
- Traits
  - Ordering, grouping, filtering
  - Compression, deduplication, etc

**Traits** represent *capabilities*.
BLOBs linked to a **vBucket** share a *trait*.



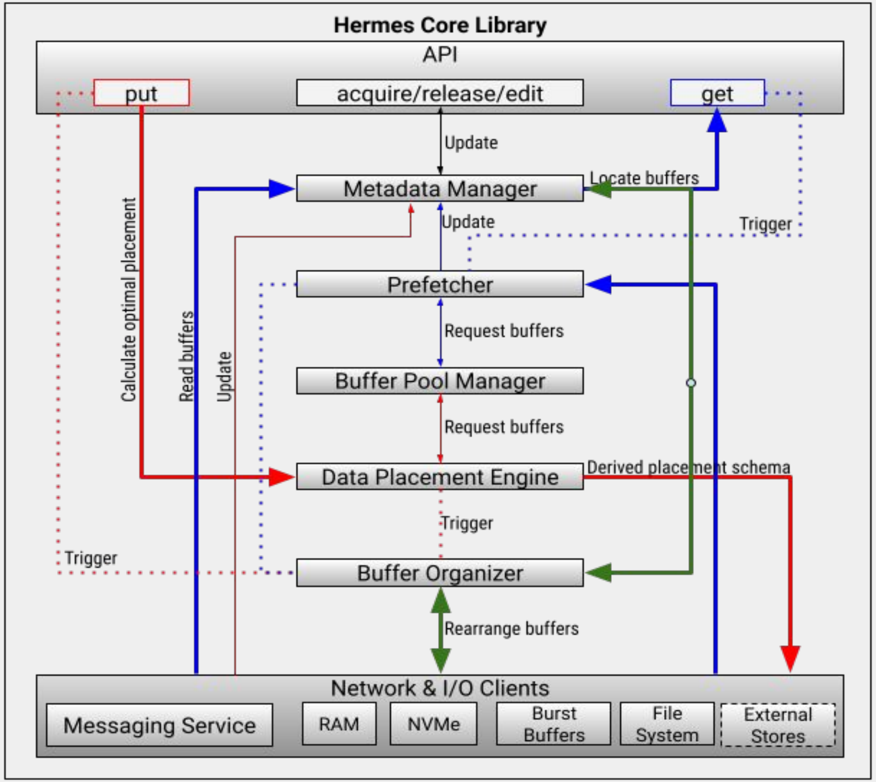
| | |
|---|---|
| Key 1 | Value 1 |
| Key 2 | Value 2 |
| ... | ... |

| | |
|---|---|
| Key 1 | Value 1 |
| Key 2 | Value 2 |
| ... | ... |

**Buckets** represent collections of
(named) **B(L)OBs** (= byte streams).

# Hermes Lib Design

- API
- Metadata Manager
- Prefetcher
- Buffer Pool Manager
- Data Placement Engine
- Buffer Organizer
- I/O Clients



# Hermes Buffering Modes

## 1 Persistent

- Synchronous
  - write-through cache,
  - stage-in
- Asynchronous
  - write-back cache,
  - stage-out

## 2 Non-Persistent

- Temporary scratch space
- Intermediate results
- In-situ analysis and visualization

## 3 Bypass

- Write-around cache

# Hermes Data Placement Policies

1

**Maximum Application Bandwidth (MaxBW)**: this policy aims to maximize the bandwidth applications experience when accessing Hermes.

2

**Maximum Data Locality**: this policy aims to maximize buffer utilization by simultaneously directing I/O to the entire DMSH.

3

**Hot-data**: this policy aims to offer applications a fast cache for frequently accessed data (i.e., hot-data).

4

**User-defined**: this policy aims to support user-defined buffering schemas. Users are expected to submit an XML file with their preferred buffering requirements.

# 1 Maximum Bandwidth

## Start from the top layer

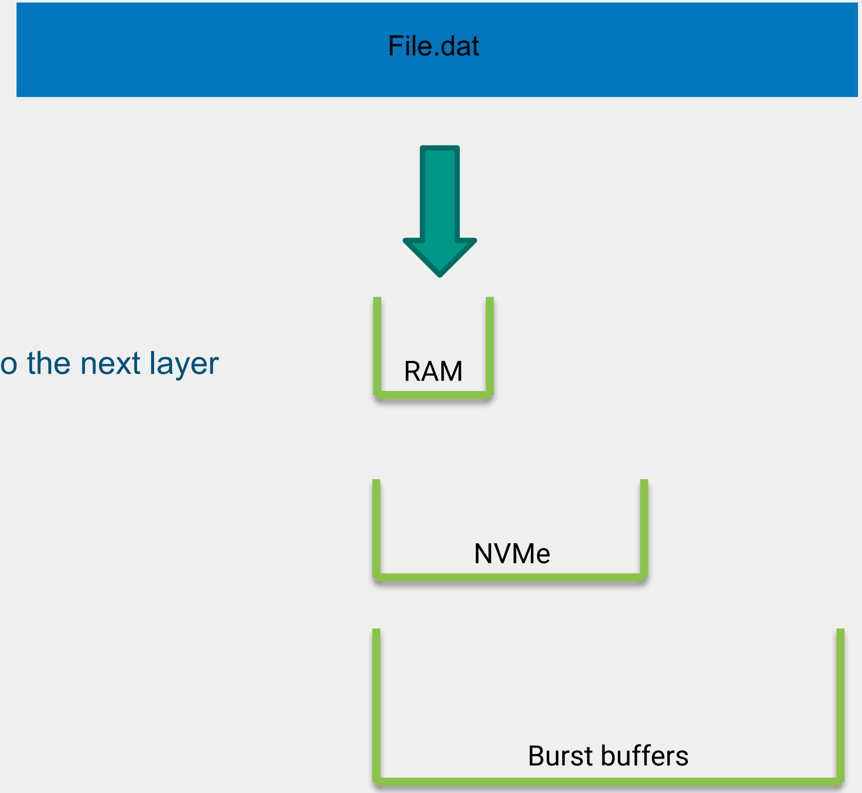
If free space > request size

place data here

If not, choose the best between

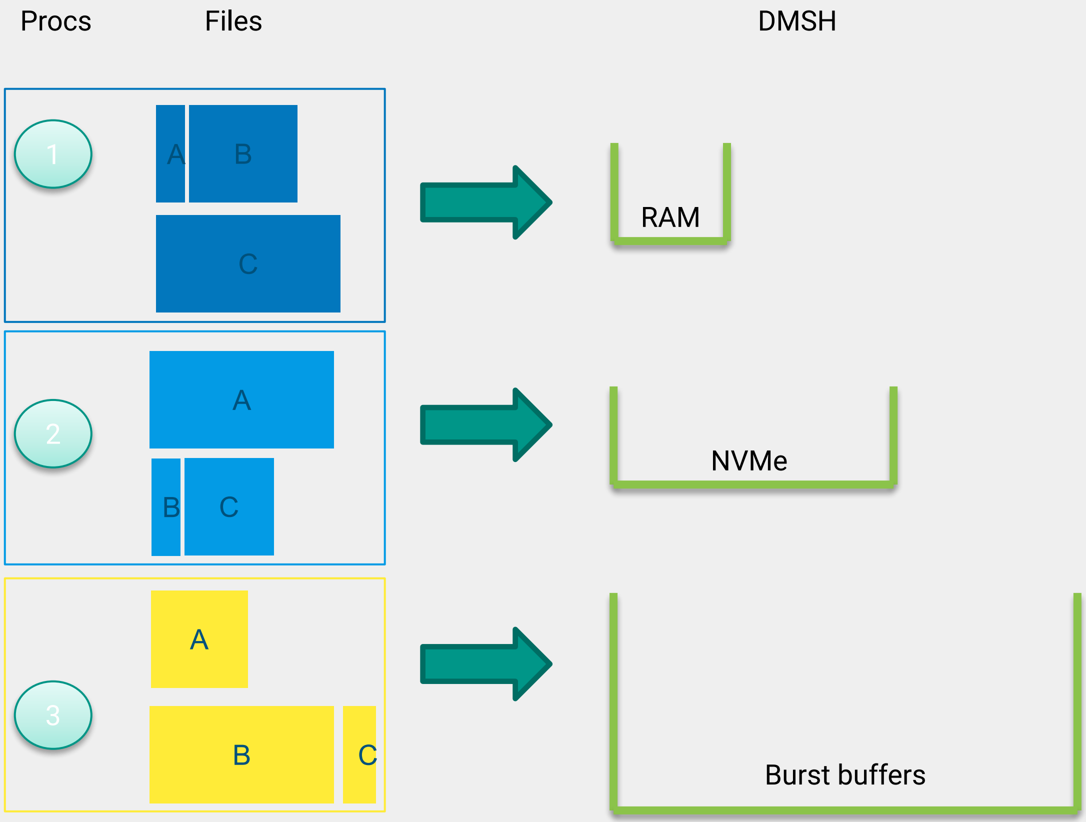
1. Place as much data as possible here and the rest to the next layer OR
2. Skip this layer and place data to the next one OR
3. First flush top layer and then place data

## Recursive process



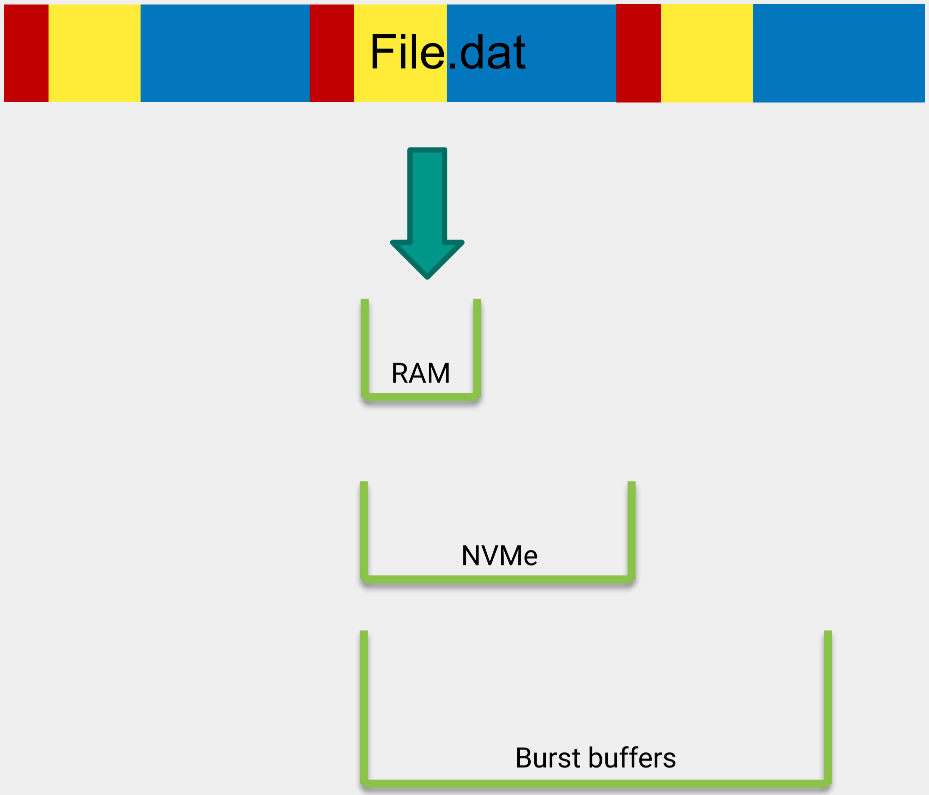
# 2 Data Locality

- Data dispersion unit:
  - POSIX files
  - HDF5 datasets
  - Etc.
- Place data based on:
  - Location of previously buffered data
  - Ratio between layers



# 3 Hot data

- Place data based on:
  - Spectrum of hot – cold data
- Higher layers hold hotter data

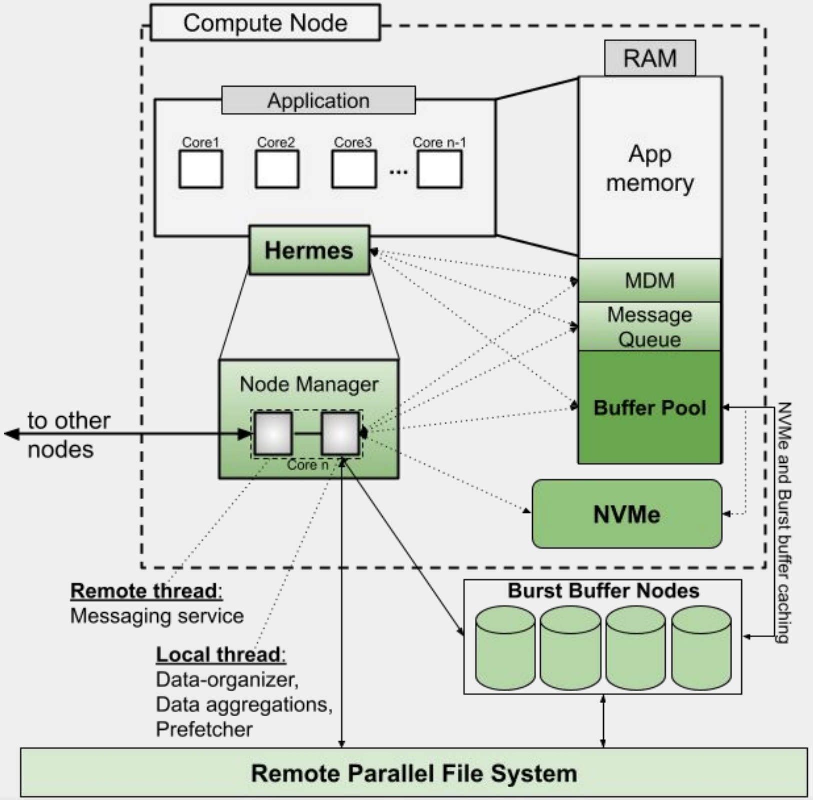


# Hermes

## Deployment

# Hermes Node Design

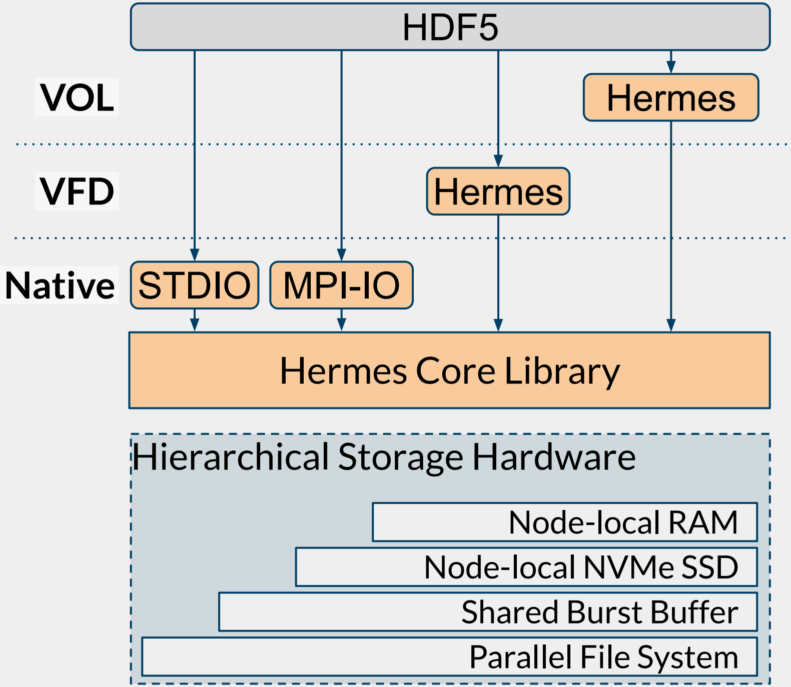
- Dedicated core for Hermes
- Node Manager
  - Dedicated multithreaded core per node
  - MDM
  - Buffer Organizer
  - Messaging Service
  - Memory management
  - Prefetcher
  - Cache manager
- RDMA-capable communication
- Can also be deployed in I/O Forwarding Layer (I/O FL)



# Hermes Adapter Layer

Applications can natively interact with Hermes using existing I/O Interfaces

- Standard Interceptors
  - STDIO
  - POSIX
  - MPI-IO
- HDF5 Level
  - Hermes VFD
  - Hermes VOL



# Deployment Models

## Collocated

- Hermes Core is part of the application.
- Synchronization is managed internally by hermes lib.
- Isolates buffering data across applications.

```
mpirun -n 1280 -f app_hf ./application
```

## Decoupled

- Hermes Core is separate from the application.
- The Hermes core needs to be running before the application.
  - Manually, or
  - as a service
- Can share buffering data across applications.

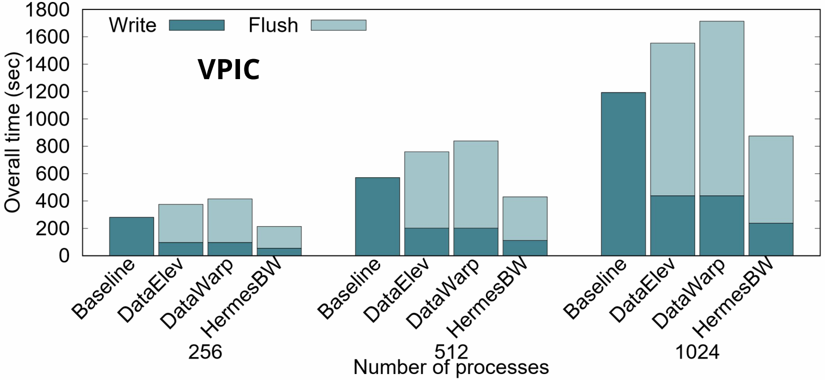
```
mpirun -n 32 -f hermes_core_hf ./hermes_core
mpirun -n 1248 -f app_hf ./application
```

Hermes

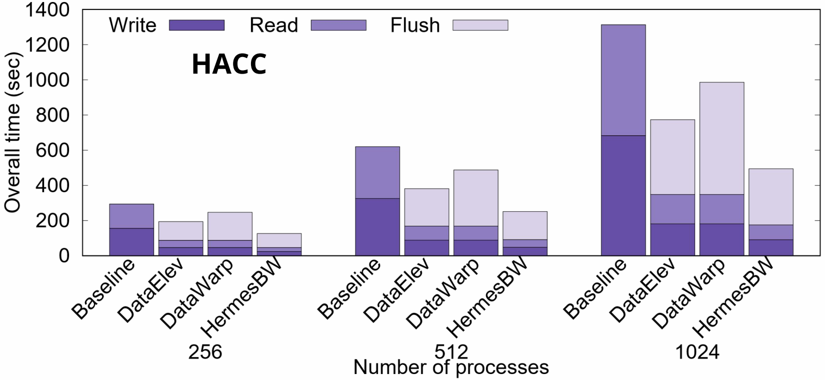
# Initial Results

# Scientific Applications

- Strong scaled up to 1024 ranks
- 16-time steps
- Metric:
  - Total I/O time (write + read + flush)
- Vector Particle-In-Cell (VPIC):
  - Uses HDF5 files
- Hardware Accelerated Cosmology Code (HACC):
  - MPI - I/O Independent



Hermes offers **5x and 2x** higher write performance on average when compared to No Buffering and state-of-the-art buffering platforms



Hermes offers **7.5x and 2x** higher read performance for repetitive patterns when compared to No Buffering and state-of-the-art buffering platforms

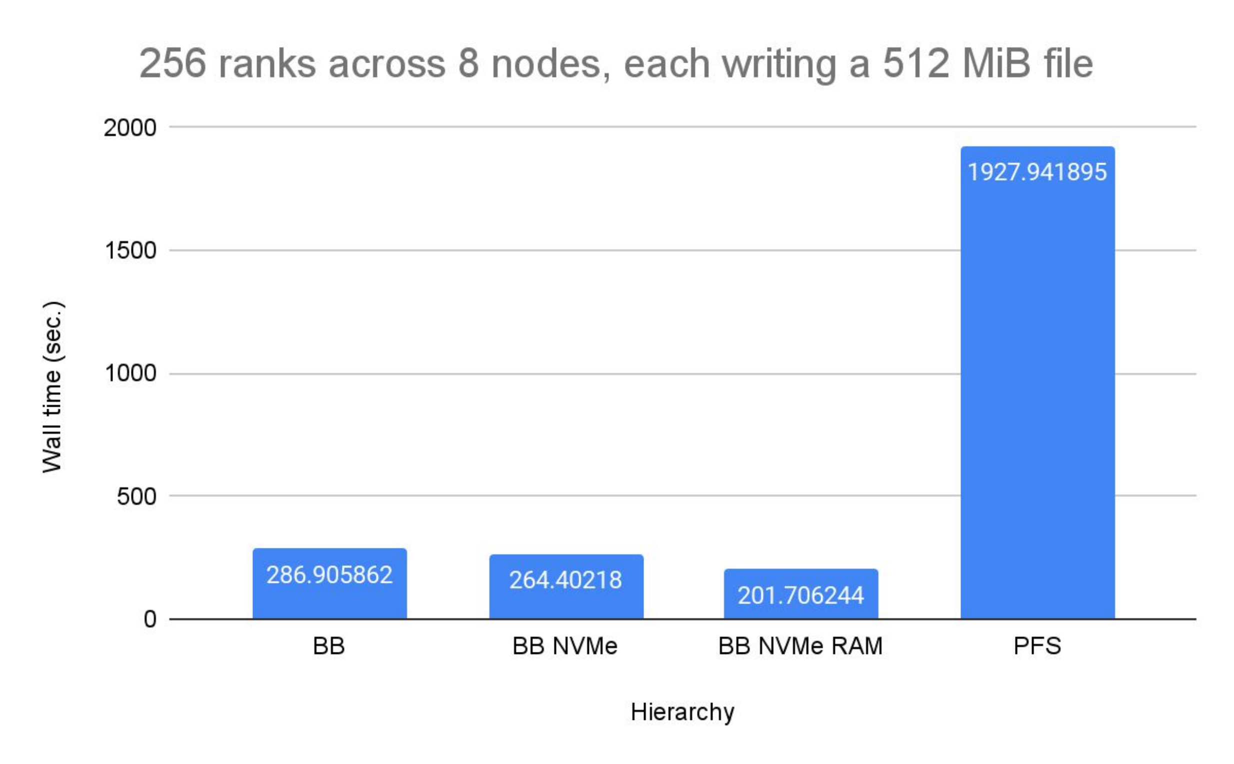
- Hermes hides data movement between tiers behind compute
- Hermes leverages the extra layers of the DMSH to offer higher BW
- Hermes utilizes a concurrent flushing overlapped with compute

Anthony Kougkas, Hariharan Devarajan, and Xian-He Sun. *Hermes: A Heterogeneous-Aware Multi-Tiered Distributed I/O Buffering System*, In Proceedings of the 27th International Symposium on High-Performance Parallel and Distributed Computing, pp. 219-230. ACM, 2018.

# Hermes Acceleration for VPIC-style Workload

VPIC-IO

- HDF5 files
- Checkpointing
- File-per-process
- Buffer the intermediate checkpoints and flush at finalize
- Remote global PFS suffers from high latency and low throughput
- Contention across processes

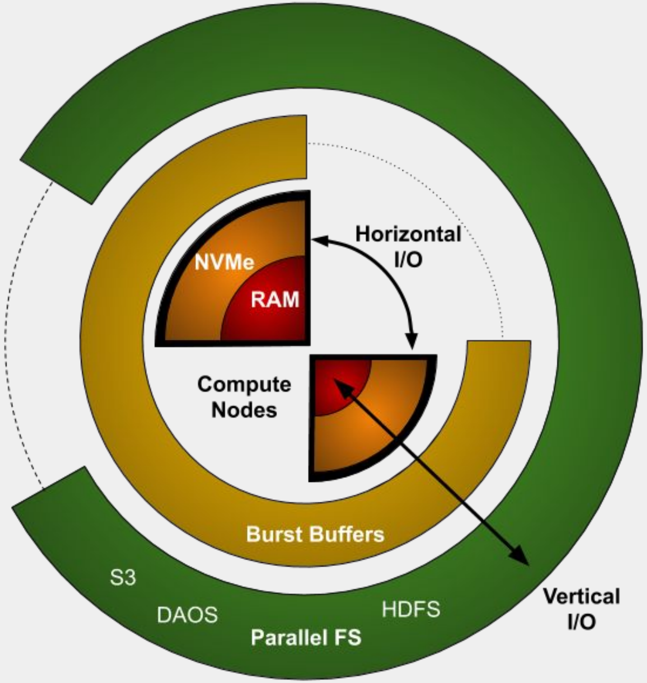


Hermes

# Tools and Services

# Hermes Container Library (HCL)

- Deep Storage Hierarchy
  - Spans multiple tiers within a node...
  - ...but also multiple nodes in the cluster
- Applications need to distribute data structures across multiple nodes.
  - Hermes Container Library (HCL)
    - H. Devarajan, A. Kougkas, K. Bateman, and X-H Sun. "HCL: Distributing parallel data structures in extreme scales." In 2020 IEEE International Conference on Cluster Computing (CLUSTER).
    - https://github.com/HDFGroup/hcl
  - We invite the community to try it out
    - And please give us feedback.



# Hermes External Services

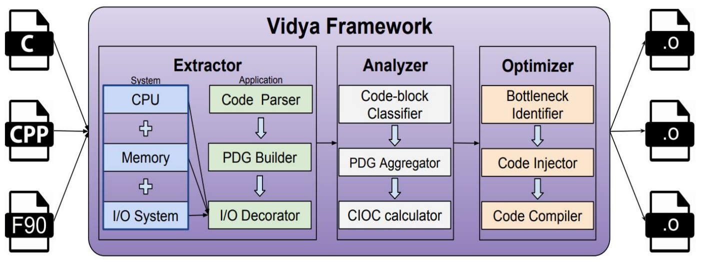
- Application Orchestrator
  - offers support in a multiple-application environment
  - manages access to the shared layers of the hierarchy
  - minimizes interference between different applications sharing a layer
  - coordinates the flushing of the buffers to achieve maximum I/O performance

Anthony Kougkas, Hariharan Devarajan, Xian-He Sun, and Jay Lofstead.
"Harmonia: An Interference-Aware Dynamic I/O Scheduler ",
In Proceedings of the IEEE International Conference on Cluster Computing 2018 (Cluster'18)

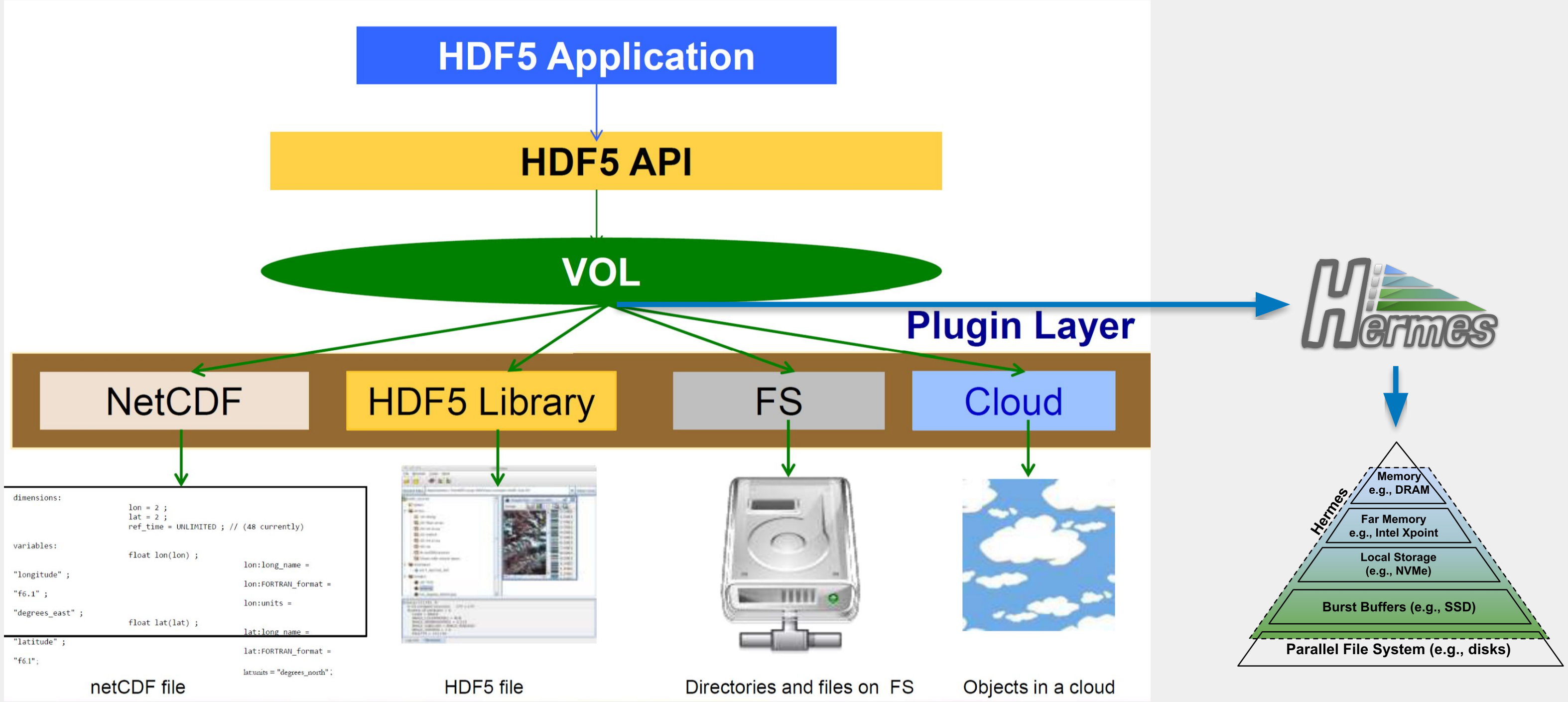
# Hermes External Services

- System Profiler
  - runs once during the initialization
  - performs a profiling of the underlying system in terms of hardware resources
  - detects the availability of DMSH and measures each layer's respective performance
  - profiles the applications and identifies incoming I/O phases
  - works together with the application coordinator (Harmonia) to detect access conflicts

Hariharan Devarajan, Anthony Kougkas, P. Challa, Xian-He Sun
*"Vidya: Performing Code-Block I/O Characterization for Data Access Optimization"*
In Proceedings of the IEEE International Conference on High Performance Computing, Data, and Analytics 2018 (HiPC'18), Bengaluru, India



# Hermes VOL plugin for HDF5 coming…


HDF5 Application
HDF5 API
VOL
Plugin Layer
NetCDF
HDF5 Library
FS
Cloud
netCDF file
HDF5 file
Directories and files on FS
Objects in a cloud
Hermes
Memory e.g., DRAM
Far Memory e.g., Intel Xpoint
Local Storage (e.g., NVMe)
Burst Buffers (e.g., SSD)
Parallel File System (e.g., disks)

```
dimensions:
                    lon = 2 ;
                    lat = 2 ;
                    ref_time = UNLIMITED ; // (48 currently)

variables:
                    float lon(lon) ;
                                        lon:long_name =
"longitude" ;
                                        lon:FORTRAN_format =
"f6.1" ;
                                        lon:units =
"degrees_east" ;
                    float lat(lat) ;
                                        lat:long_name =
"latitude" ;
                                        lat:FORTRAN_format =
"f6.1";
                                        lat:units = "degrees_north" ;
```

Hermes

# Q&A

# Q&A

Q: The Data Placement Engine (DPE) policies rely on the fact that users know the behavior of their application in advance which can be a bold assumption.

A: Hermes uses profiling tools beforehand to learn about the application’s behavior and thus, tune itself. Our work, Vidya, further solves this issue by automating the whole process analyzing the source code.

Q: How does Hermes integrate to modern HPC environments?

A: As of now, applications link to Hermes (re-compile or dynamic linking). An HDF5 VOL plugin is underway. We also intend to incorporate Hermes to the system scheduler and thus, include buffering resources into batch scheduling.

# Q&A

Q: How are Hermes' policies applied in multi-user environments?

A: Hermes' Application Orchestrator is designed for multi-tenant environments. Our work, Harmonia, has been tested and proven it can mitigate the contention between competing applications.

Q: What is the impact of the asynchronous data reorganization?

A: In scenarios where there is some computation in between I/O (i.e., most realistic application workloads), asynchronicity works great.

# Q&A

Q: What is Hermes’ metadata size?

A: In our evaluation, for 1 million user files, the metadata created by Hermes were 1.1GB.

Q: Is Hermes open source?

A: Yes! The 1st public beta release is scheduled for Nov 1st. We are currently improving the quality of the code and writing documentation.

# Q&A

Q: How to balance the data distribution across different compute nodes especially when the I/O load is imbalanced across nodes?

A: Hermes' System Profiler provides the current status of the system (i.e., remaining capacity, etc) and DPE is aware of this before it places data in the DMSH. It is up to Hermes' Engine to balance the load.

Q: How to minimize extra network traffic caused by horizontal data movement?

A: Horizontal data movement can be in the way of the normal compute traffic. RDMA capable machines can help. We also suggest using the "*service class*" of the Infiniband network to apply priorities in the network.

# Q&A

Q: How is the limited RAM space partitioned between applications and Hermes?

A: Totally configurable by the user. Typical trade-off. More RAM to Hermes can lead to higher performance. No RAM means skip the layer.

Q: What is Hermes' DPE complexity?

A: In the order of number of tiers.

# Q&A

Q: How difficult is to tune Hermes' configuration parameters?

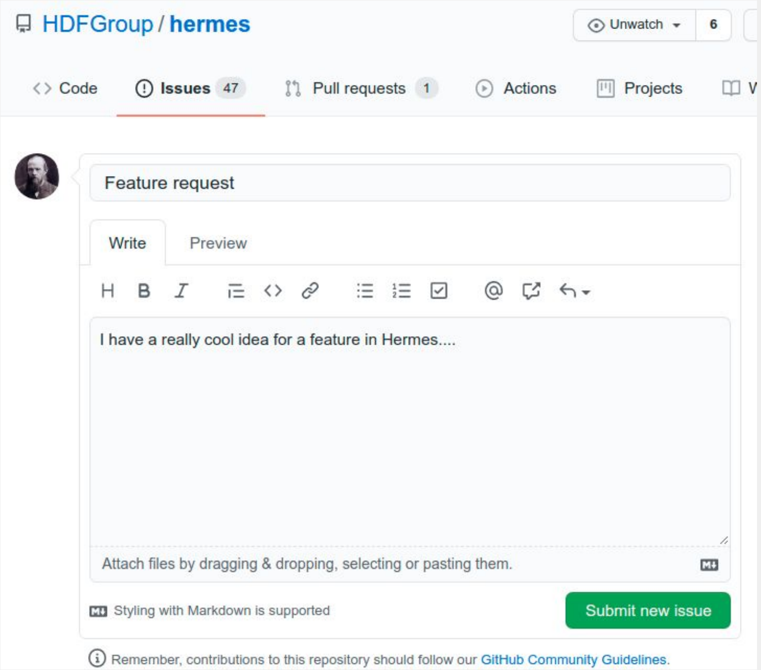
A: We expose a configuration_manager class which is used to pass several Hermes' configuration parameters. ML-assisted tuner is planned to be added.

Q: What is Hermes API?

A: Hermes captures existing I/O calls. Our own API is really simple consisting of hermes::get(…, flags) and hermes::put(…,flags). Flag system implements active buffering semantics (currently only for the burst buffer nodes).

# How Can I Get Involved?

- Github repo: https://github.com/HDFGroup/hermes
- Create an issue to submit feedback, use cases, or feature requests.
- Note: Hermes is still under active development with target beta release this November



HDFGroup / **hermes**

Feature request

I have a really cool idea for a feature in Hermes....

Attach files by dragging & dropping, selecting or pasting them.

Styling with Markdown is supported

Remember, contributions to this repository should follow our GitHub Community Guidelines.

Hermes

# Publications

# Publications

- Conferences:
  - Kougkas, A; Devarajan, H; and Sun X-H. "*Hermes: a heterogeneous-aware multi-tiered distributed I/O buffering system*." In Proceedings of the 27th International Symposium on High-Performance Parallel and Distributed Computing, pp. 219-230. 2018.
  - Devarajan, H; Kougkas, A; Bateman, K; Sun, X.-H. "*HCL: Distributing Parallel Data Structures in Extreme Scales*," 2020 IEEE International Conference on Cluster Computing (CLUSTER),
  - Devarajan, H; Kougkas, A; Logan, L; and Sun, X.-H. "*HCompress: Hierarchical Data Compression for Multi-Tiered Storage Environments,*" 2020 IEEE International Parallel and Distributed Processing Symposium (IPDPS), New Orleans, LA, USA, 2020,
  - Devarajan, H; Kougkas, A; Sun, X.-H. "*HFetch: Hierarchical Data Prefetching for Scientific Workflows in Multi-Tiered Storage Environments*," 2020 IEEE International Parallel and Distributed Processing Symposium (IPDPS), New Orleans, LA, USA, 2020,
  - Devarajan, H; Kougkas, A; Sun, X.-H. "*HReplica: A Dynamic Data Replication Engine with Adaptive Compression for Multi-Tiered Storage*," 2020 IEEE International Conference on Big Data (Big Data)

# Publications

- Journals:
    - Kougkas, A; Devarajan, H; Sun, X.-H., "*I/O Acceleration via Multi-Tiered Data Buffering and Prefetching*", In Journal of Computer Science and Technology (JCST) 2020. vol 35. no 1. pp 92-120. 10.1007/s11390-020-9781-1
    - Kougkas, A; Devarajan, H; Sun, X.-H., "*Bridging Storage Semantics using Data Labels and Asynchronous I/O*", in Transactions on Storage (TOS), Vol 16, No 4, Article 22, 2020. DOI:https://doi.org/10.1145/3415579

Hermes

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# Questions?

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