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IRIS: I/O Redirection via Integrated Storage

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Special thanks to Dr. Shuibing He who kindly accepted to help us present this work.

Agenda

- Background
- Approach
- Design
- Evaluation
- Conclusions
- Q&A

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Highlights of this work

Design of several mapping algorithms
- Files to objects
- Objects to files

Design and implementation of IRIS
- Cross-storage integrated data access
- Programming convenience and efficiency

Evaluation results showed IRIS can offer
- Performance boost up to **7x**
- Minimal overheads

Towards I/O convergence between HPC and HPDA storage subsystems

Different Communities - Cultures - Tools

lustre File System

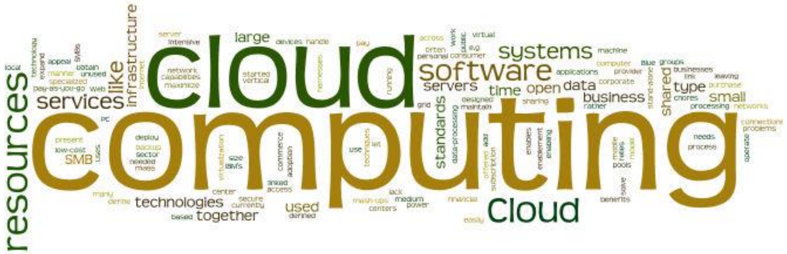
IBM GPFS

OrangeFS

panasas

The tools and cultures of HPC and BigData analytics have diverged, to the detriment of both; **unification** is essential to address a spectrum of major research domains.

- D. Reed & J. Dongarra



cassandra

mongoDB

riak

levelDB

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Storage in HPC

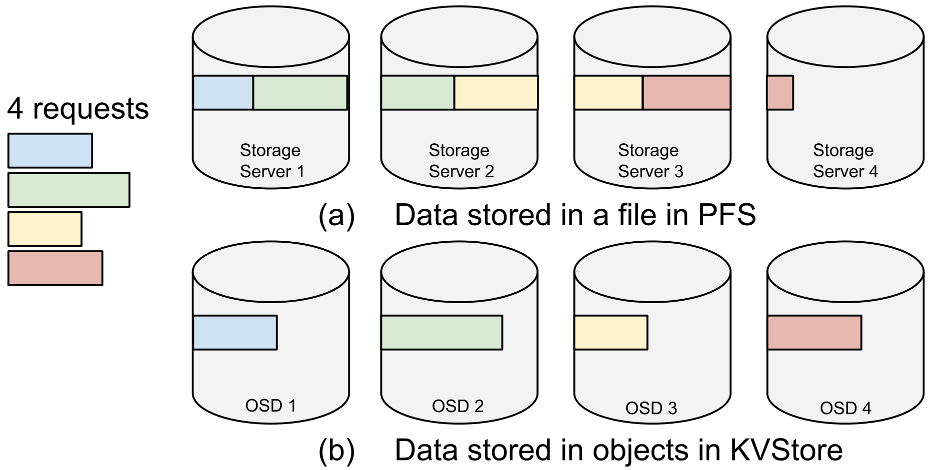
- Parallel File Systems (PFS):
  - Peak performance: ~2000GiB/s
  - Capacity: >70PiB
- Interfaces:
  - POSIX, MPI-IO, HDF5, etc.,
- Limitations:
  - Scalability, complexity, metadata services
  - Small file access, data synchronization, etc.,

#	site.name	site.storage system.net capacity	site.storage system.peak read	site.storage system.peak write	site.storage system.software
		in PiB	*in GiB/s*	*in GiB/s*	
1	kaust	16.96	1955.78	1955.78	Lustre,Cray Tiered Adaptive Storage (TAS)
2	jcahpc	24.10	1918.52	1918.52	Lustre,Lustre
3	riken	39.77	3187.23	1510.85	FEFS,Lustre,FEFS,staging
4	ncsa	27.60	1158.00	1158.00	Lustre,HPSS
5	nscg	14.40	1100.00	1100.00	H2FS
6	llnl	48.85	1000.00	1000.00	Lustre,ZFS
7	ornl	28.00	1000.00	1000.00	Lustre
8	nersc	30.00	700.00	700.00	Lustre,DataWarp
9	jamstec	19.62	407.92	407.92	ScaTeFS,NFS,ScaTeFS,NFS
10	nscc	17.76	288.00	288.00	

I/O 500 List (Nov 2017)

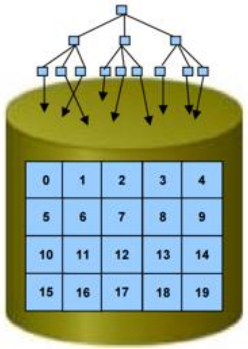
Data Distribution

PFS	KVS
Uses fixed-size stripes	Key-value pair as a single object
Distributes data in a fixed manner(e.g. round robin)	Distributes objects to all available nodes
Need for sub-request synchronization	No need to synchronize anything
Metadata must include the directory tree, permissions, data's physical location on disks, etc.,	Flat namespace with a hash table that keeps the mapping between keys and values



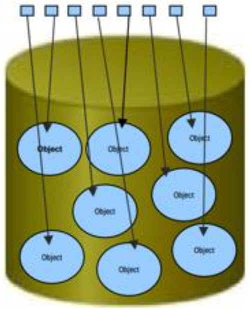
Data models and Storage systems

- File-based storage systems
  - POSIX-I/O
    - fwrite(), fread(),
  - MPI-I/O
    - MPI_File_read(), MPI_File_Write()
  - High-level I/O libraries
    - e.g., HDF5, pNetCDF, MOAB etc



Category	Object Storage	File Storage
Data unit	Objects	Files
Update	Create new object	In-place updates
Protocols	REST and SOAP	NSF with POSIX
Metadata	Custom	Fixed attributes
Strengths	Scalability	Simplified access
Limitations	Frequent updates	Heavy metadata
Performance	High throughput	Streaming of data

- Object-based storage systems
  - REST APIs,
  - get(), put(), delete()
    - Amazon S3,
    - OpenStack Swift
    - NoSQL DBs



- No "one-storage-for-all" solution.
- Each system performs great for certain workloads.
- Unification is essential.

Challenges of I/O Convergence

Gap between	traditional file-based storage	modern scalable data frameworks
Architectural differences	programming models	software tools
Lack of management	heterogeneous data resources	diverse global namespaces

Our Thesis

A radical departure from the existing software stack for both communities is not realistic and	**future software design and architectures will have to raise the abstraction level.**
We aim to design and develop a middleware system which can	**bridge the semantic and architectural gaps.**
We envision a storage system the offers a data path agnostic to the underlying data model and	**that leverages each subsystem's strengths while complementing each other for known limitations.**

Introducing

IRIS: I/O Redirection via Integrated Storage

IRIS creates a unified “storage language” to bridge the two very different compute-centric and data-centric storage camps.

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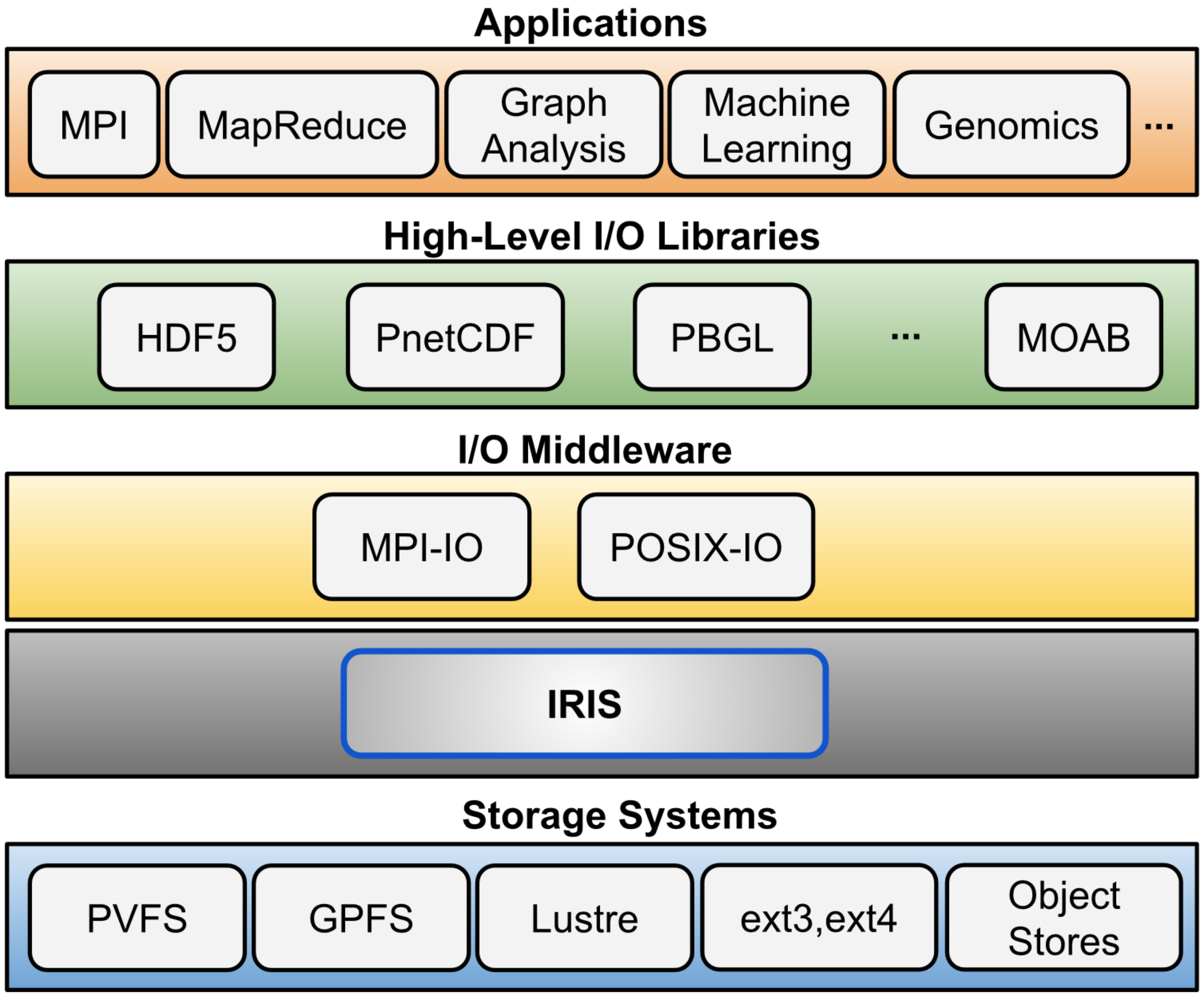
IRIS Design

- Middle-ware library
- Wrap-around I/O calls
- Written in C++, modular design
- Non-invasive: plugin nature
  - Link with applications (i.e., re-compile or LD_PRELOAD)
- Existing datasets loaded upon bootstrapping via crawlers
- Directory operations not supported
- Deletions via invalidation



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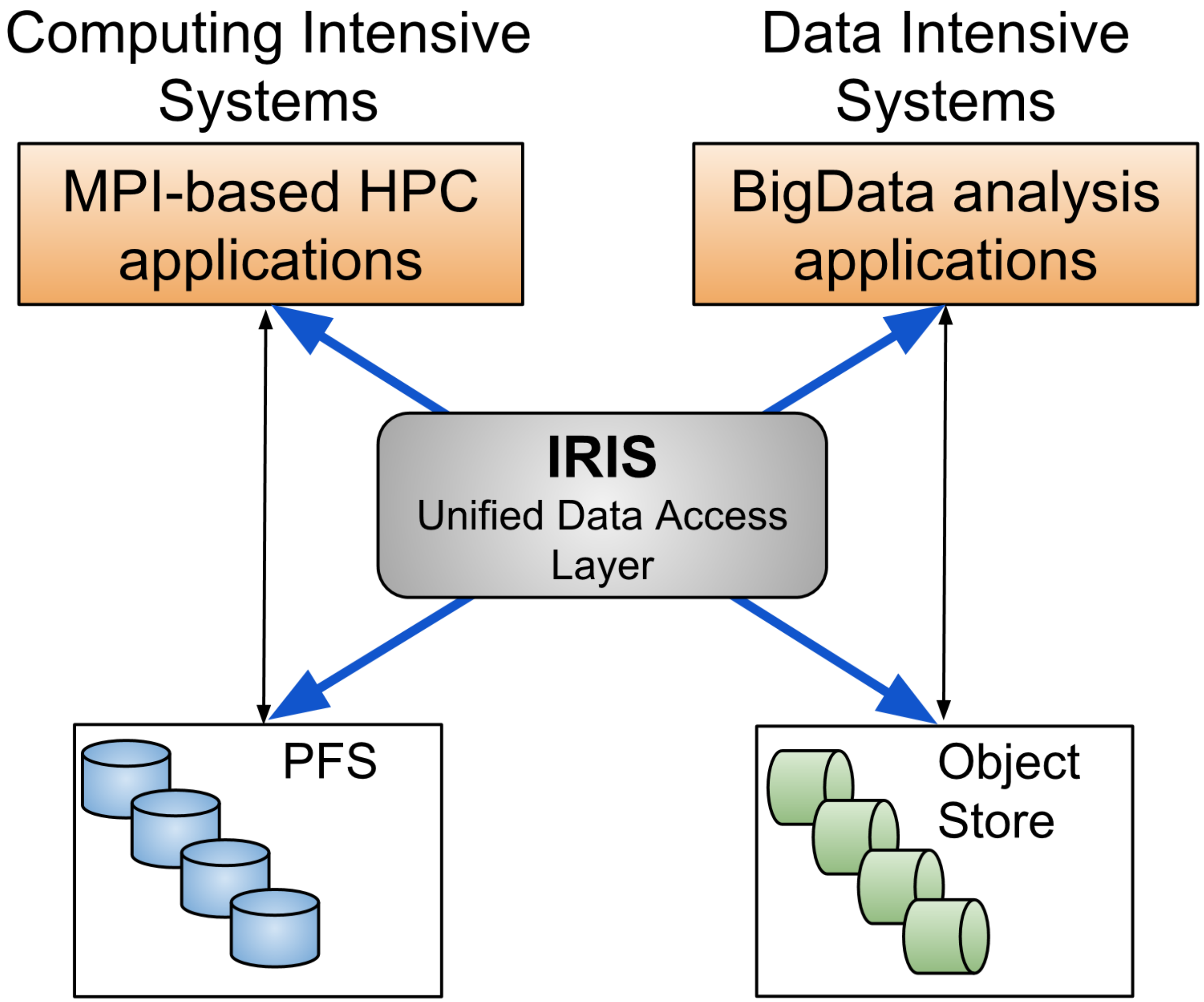
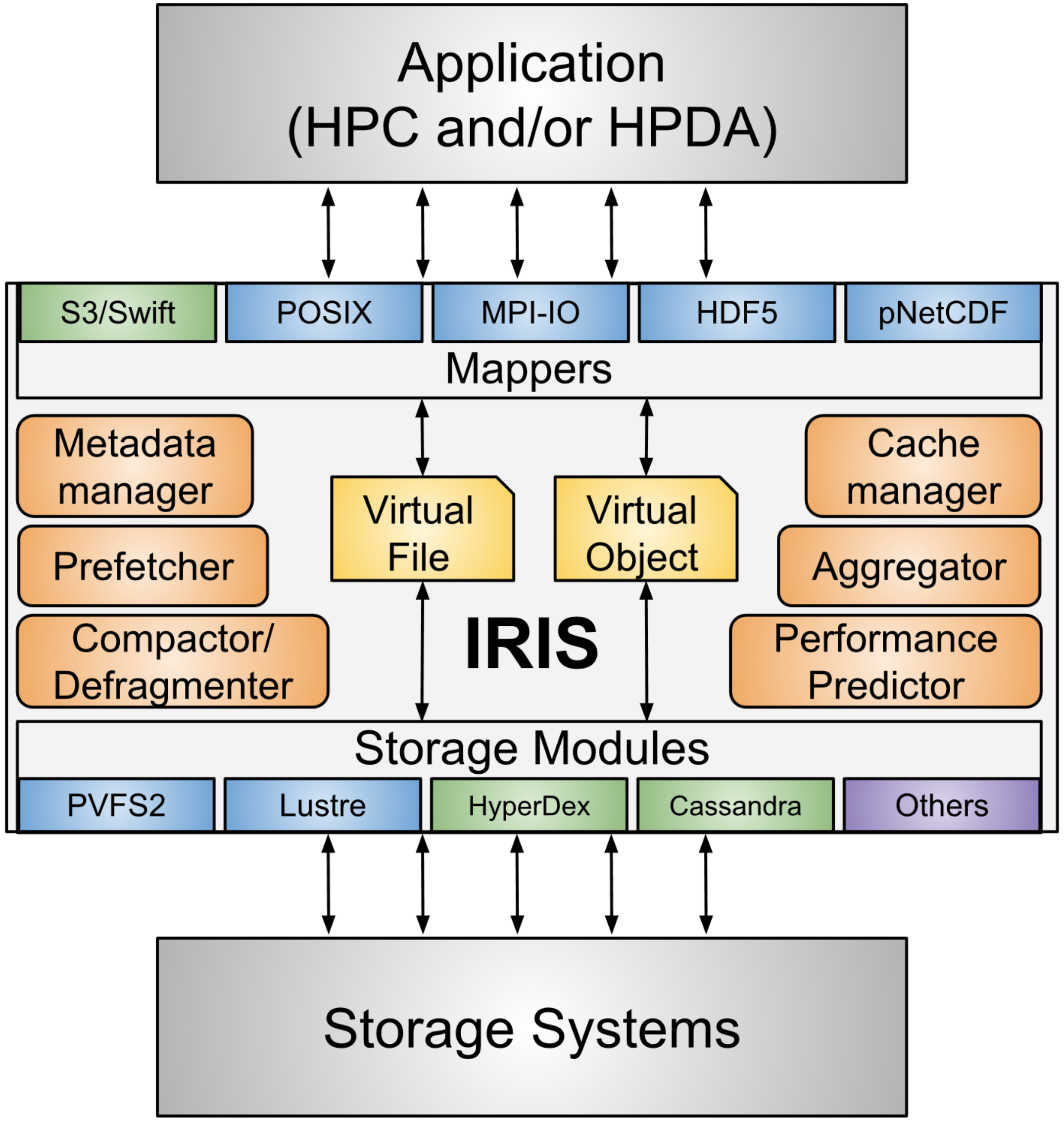
IRIS Objectives

- Enable MPI-based applications to access data in an Object Store without user intervention.
- Enable HPDA-based applications to access data in a PFS without user intervention.
- Enable a hybrid storage access layer agnostic to files or objects.



IRIS Architecture

- Decouples the storage interface
- Abstracts the storage subsystem
- Modular design allows addition of more mappers and modules
- PFS and KVS equal “citizens”
- Optimized for high performance



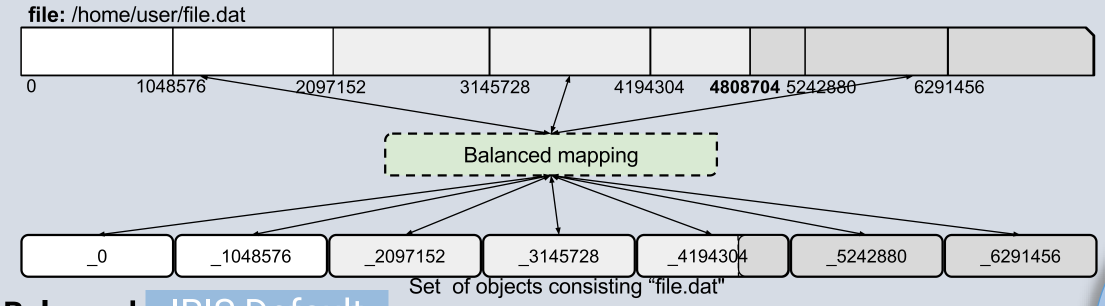
Virtual File (Container)
Name: string
FilePointer: size_t
Size: size_t
Objects: map<VirtualObjects>
InvalidObjects: map<VirtualObjects>

Virtual Object
Name: string
Size: size_t
OffsetInContainer: size_t
Data: void*
LinkedObjects: vector<VirtualObjects>

Mapping Files to Objects

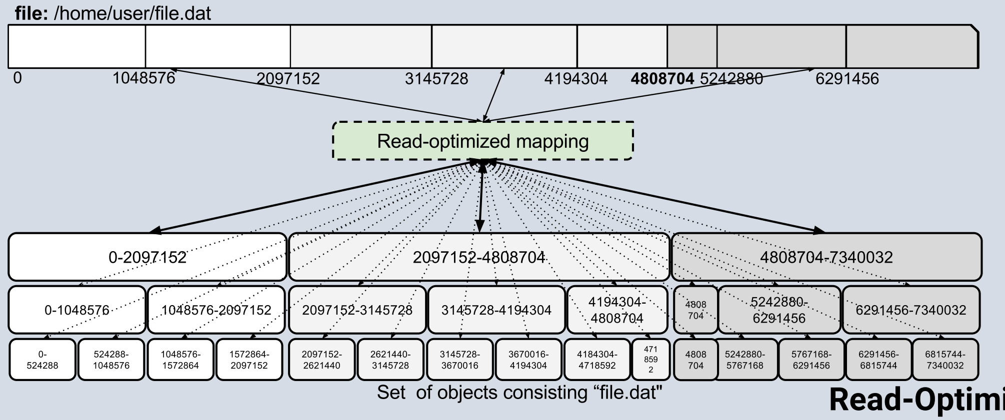
Balanced — IRIS Default

- Ideal for mixed workloads (both fread() and fwrite()).
- File is divided into predefined, fixed-size, smaller units of data, called **buckets**.
- Bucket size is a tunable parameter
- Natural mapping of buckets-to-objects.

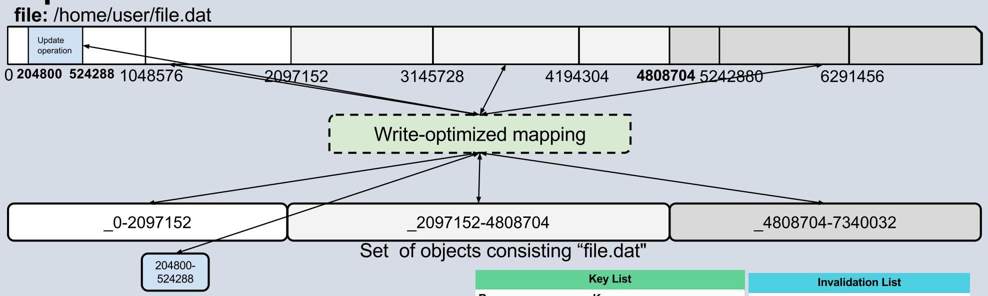


Read-Optimized

- Ideal for read-only or read-heavy (e.g., >90% read) workloads.
- Each write creates a plethora of new various-sized objects.
- Equivalent to replication: sacrifice disk space to increase availability for reads.
- All available keys in a range of offset are kept in a B+ tree.



Write-Optimized

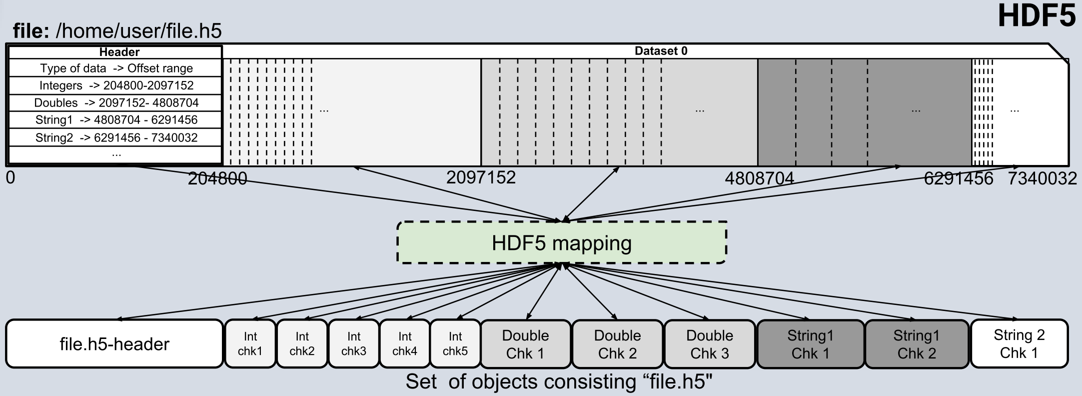


Key List	
Range	Keys
0 - 2097152	file.data_0-2097152
2097152 - 4808704	file.data_2097152-4808704
4808704 - 7340032	file.data_4808704-7340032
0 - 2097152	file.data_204800-524288

Invalidation List	
Key	Range
File.dat_0-2097152	204800 - 524288

- Ideal for write-only or write-heavy (e.g., >80% write) workloads.
- Each request creates a new object.
- A mapping of offset ranges to available keys is kept in a B+ tree for fast searching.
- Update operations create a new object and invalidate ensuring consistency.

HDF5

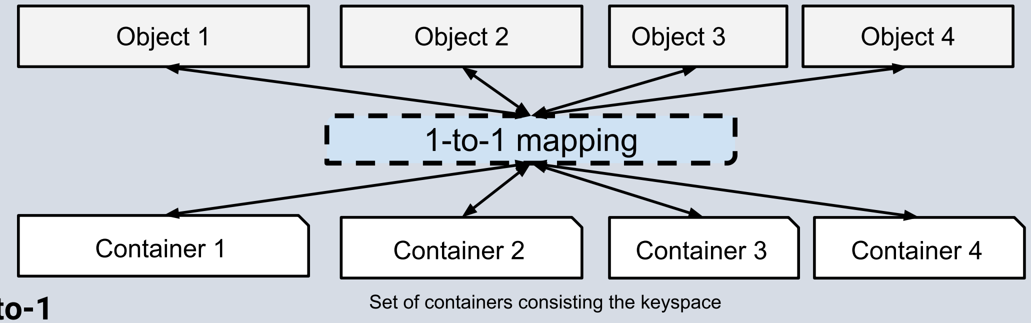


- Exploit rich metadata info HDF5 offers to create better mappings.
- Each HDF5 file creates 2 types of objects: header object and data object.
- Variable-sized data objects are created based on each dataset's dimensions and datatype.

Mapping Objects to Files

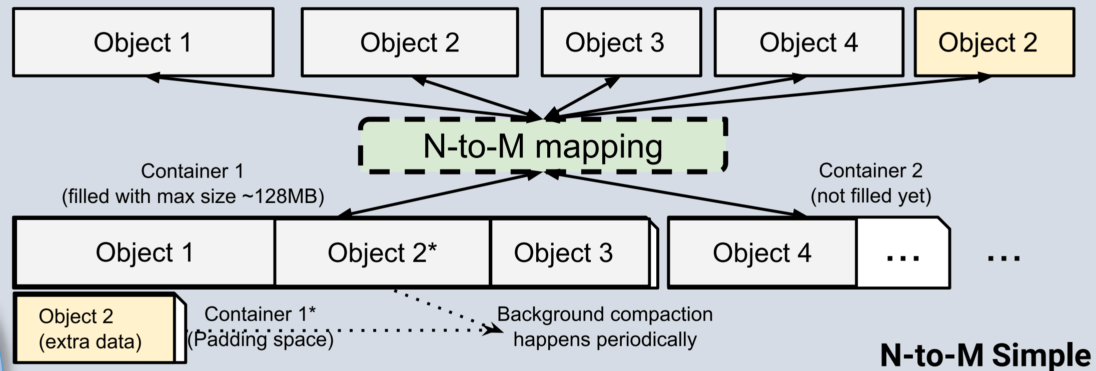
1-to-1

- Each object is mapped to a unique container.
- Ideal for accessing existing datasets.
- Good performance for relatively small number of objects.

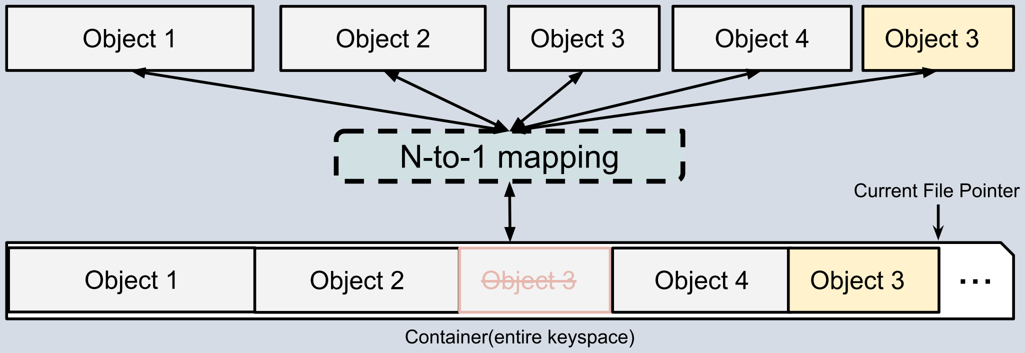


N-to-M Simple

- A collection of objects is mapped to a collection of containers.
- Threshold to create new containers (default every 128MB) bounding the total number of containers.
- Special container-> update container for padding.

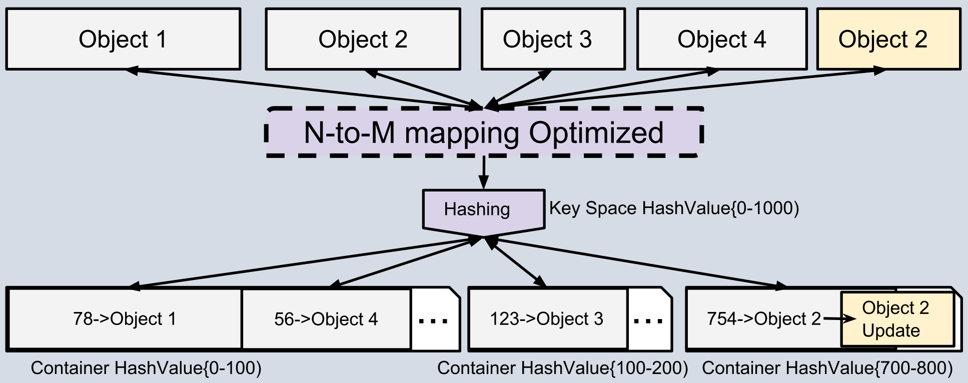


N-to-1

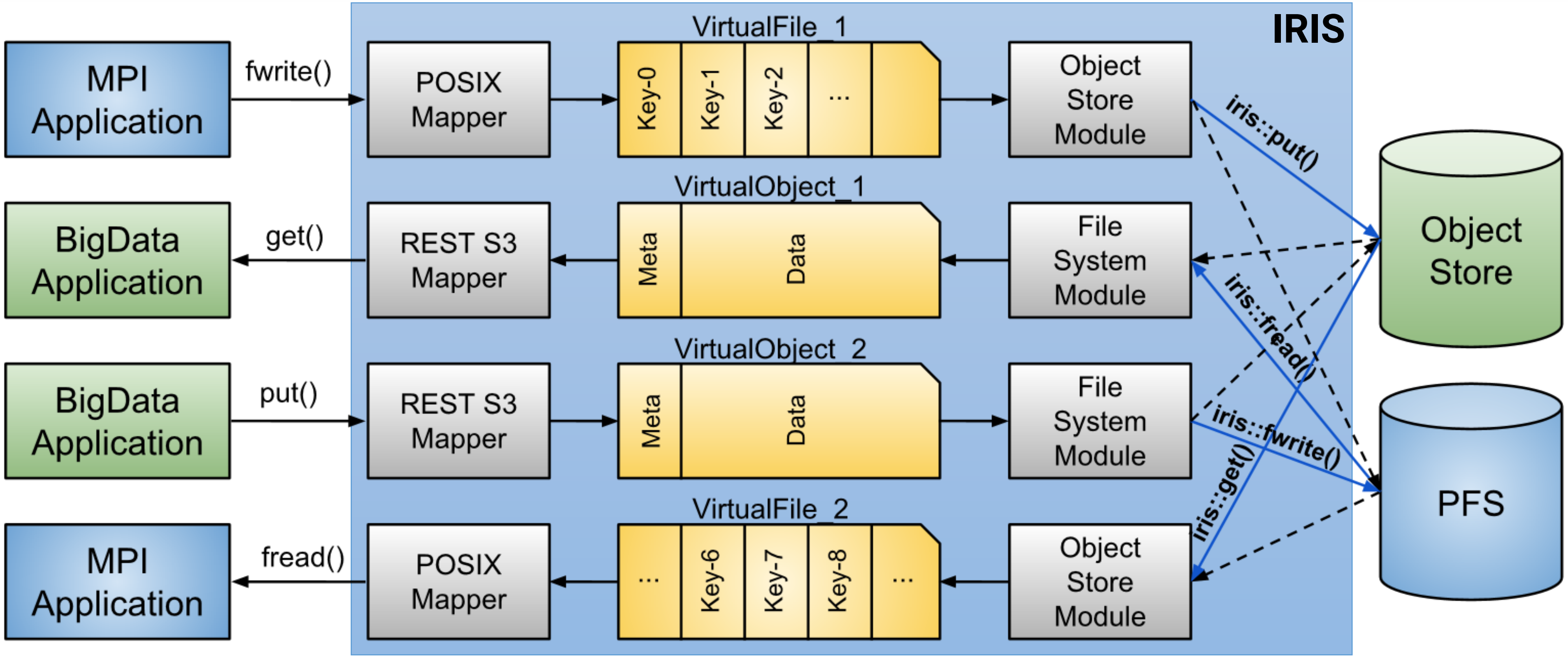


- Entire keyspace is mapped to one container.
- Virtual objects are written sequentially.
- Updates are appended at the end of the file while invalidating the previous object.
- Indexing is important for faster get() operations.

IRIS Default N-to-M Optimized

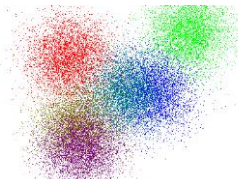


- Objects are first hashed into a key space and then mapped to container
- Containers are created according to a range of hash values and their size is flexible
- Update operations write at the end of the container, invalidating previous object.
- Periodic container defragmentation to save storage space.



Data Flow Example

- IRIS enables new data paths
- Abstracts the underlying storage solution



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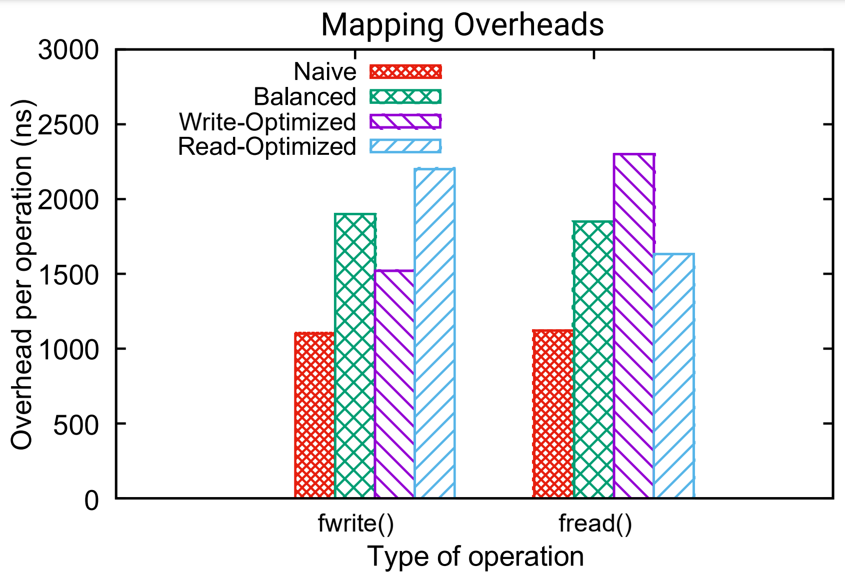
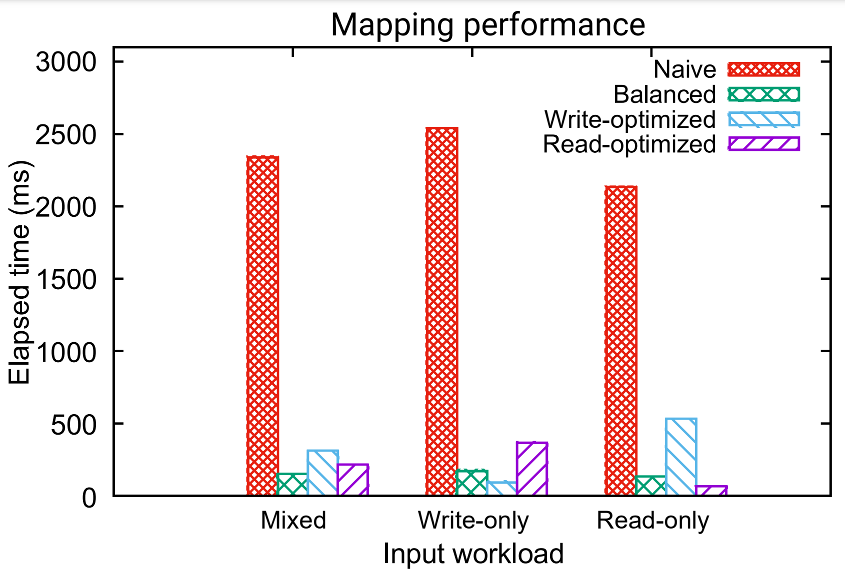
Testbed and Configurations

- Testbed: Chameleon System
- Appliance: Bare Metal
- OS: Centos 7.1
- Storage:
  - OrangeFS 2.9.6
  - MongoDB 3.4.3
- MPI: Mpich 3.2
- Programs:
  - Synthetic benchmark
  - Montage
  - CM1 from NCSA
  - WRF
  - LAMMPS
  - K-means
  - LANL anonymous scientific simulation



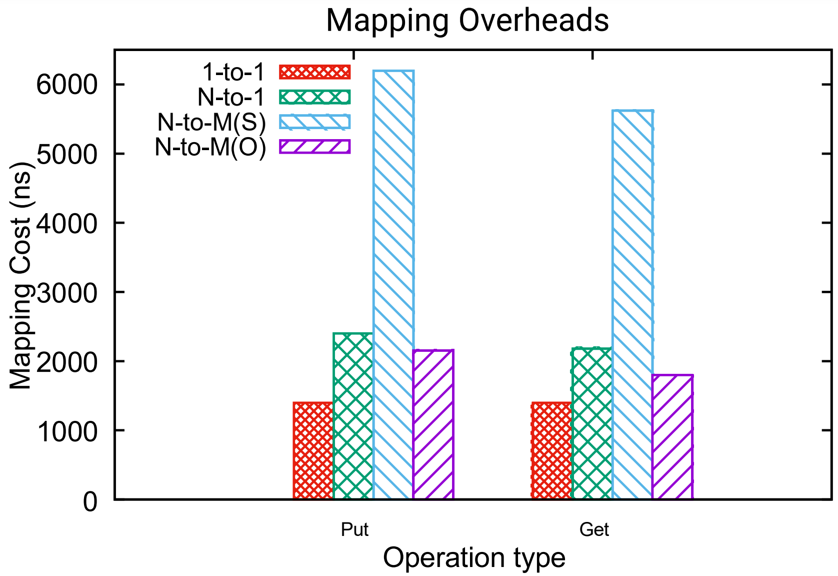
- Input: 65536 POSIX calls
- Output: Average time spend in mapping in ns (per operation)
- Naïve: simple 1-file-to-1-object
- ~0.0050% of the overall execution time (Mapping time over I/O time)



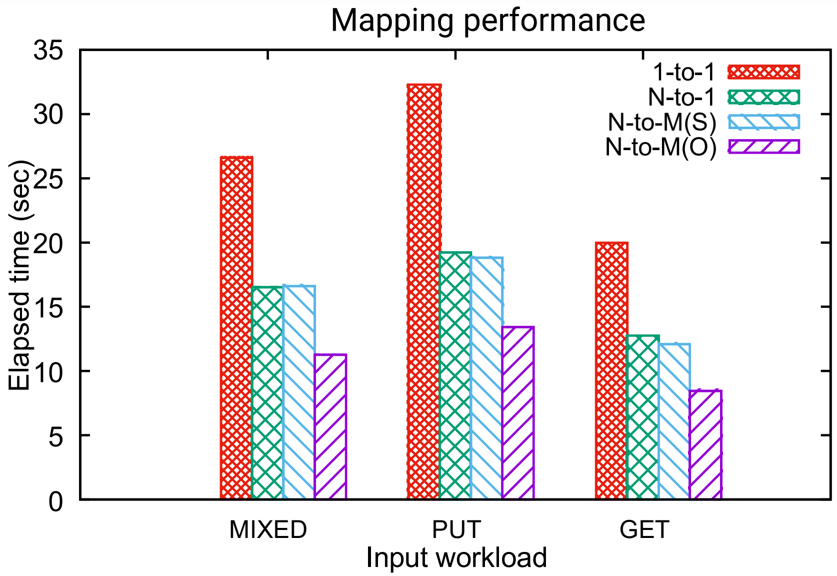
- Request size: 1MB, Total I/O: 32MB, Output: Execution time in ms
- 15x speedup for Balanced and mixed input
- 32x speedup for Read-opt and read-only input
- 27x speedup for Write-opt and write-only input

Mapping evaluation (files-to-objects)

- Overheads are kept to minimum: 2000-3500ns on average or **0.005%**
- Our mapping algorithms outperform the naïve approach by **15-32x**



- Input: 128K objects of 64KB
- Output: Average time spend in mapping in ns (per operation)
- 1-to-1 simplest with lower cost
- N-to-M-Optimized only 2000ns



- Workload: 4GB total I/O, Object size: 64KB, Output: Overall time in seconds
- Flow for mixed: 1GB write, 1GB read, 1GB update followed by 1GB read
- 1-to-1 suffers from large number of files
- N-to-M-Optimized performed more than 2x faster

Mapping evaluation (objects-to-files)

- Overheads are kept to minimum: 1300-6000ns on average or **0.008%**
- Our mapping algorithms outperform the naïve approach by **15-32x**

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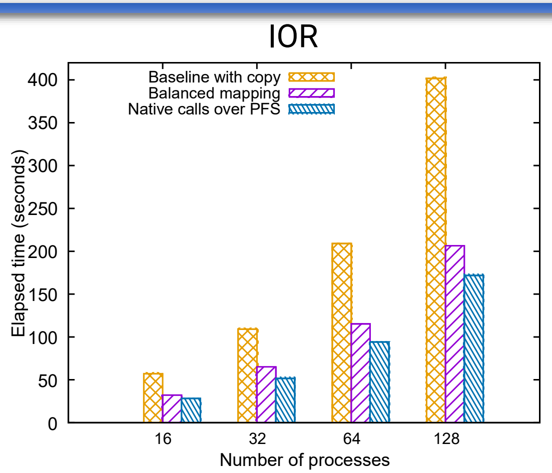
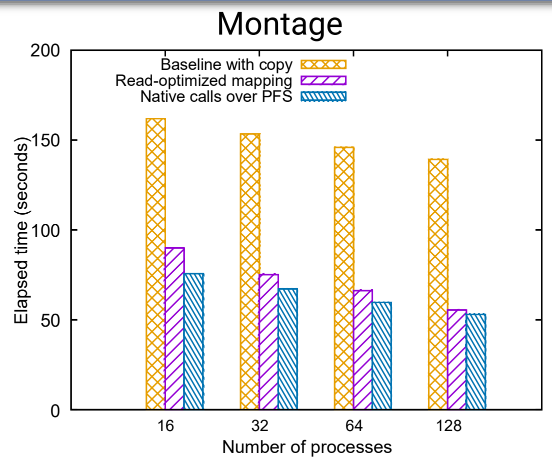
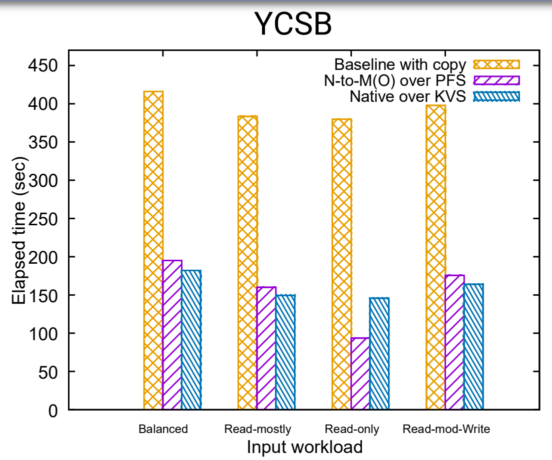


- 4 client - 4 servers
- MPI-IO, Blk_size=2MB, Transfer size = 512KB, Total I/O = 512MB per process, File-per-process, DirectIO
- Output: Execution time in seconds
- Baseline: first copy the input files from MongoDB to OrangeFS and then run

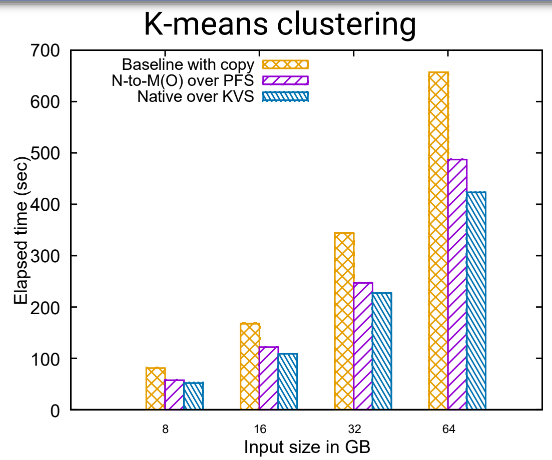


- 4 client - 4 servers
- POSIX-I/O, Total I/O = 24GB, File-per-process, OS cache disabled and flushed before
- Output: Execution time in seconds
- Baseline: first copy the input files from MongoDB to OrangeFS and then run

Files-to-Objects



- Workloads:
  - Balanced: 50% reads and 50% writes
  - Read-mostly: 90% read and 10% writes
  - Read-only: 100% read
  - Read-modify-write
- Total I/O 64GB in 64KB objects
  - Data are copied into the Redis and then run the test natively



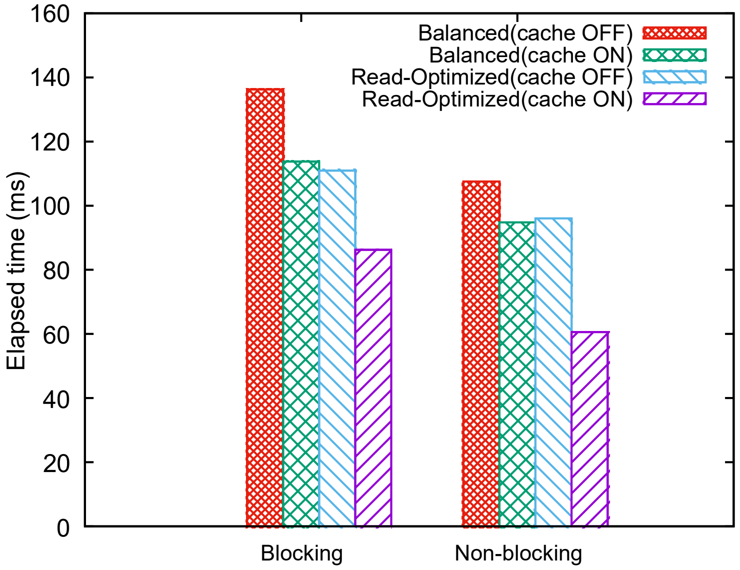
- Offline data preloading
- Baseline flow:
  - Data are copied into the Redis and then run natively
- Minimal overhead
  - 57 sec over 52 sec natively for 8GB

Objects-to-Files

Mapping Performance (real workloads)

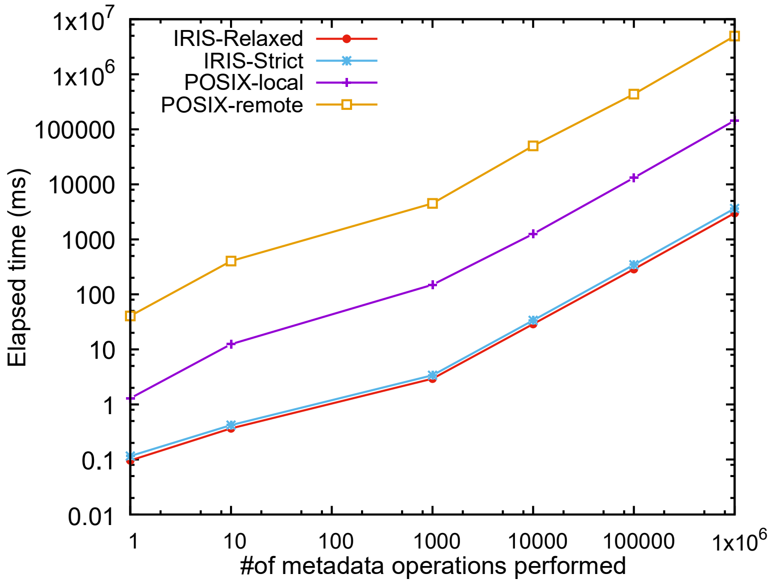
With careful mapping between the two data formats,
IRIS demonstrates **more than 2x speedup**

Prefetcher



- Blocking -> synchronous, Non-blocking-> asynchronous
- Cache ON/OFF reflects caching previous write operations
- A combination of caching and non-blocking shows **2x performance gain**

MDM (POSIX)



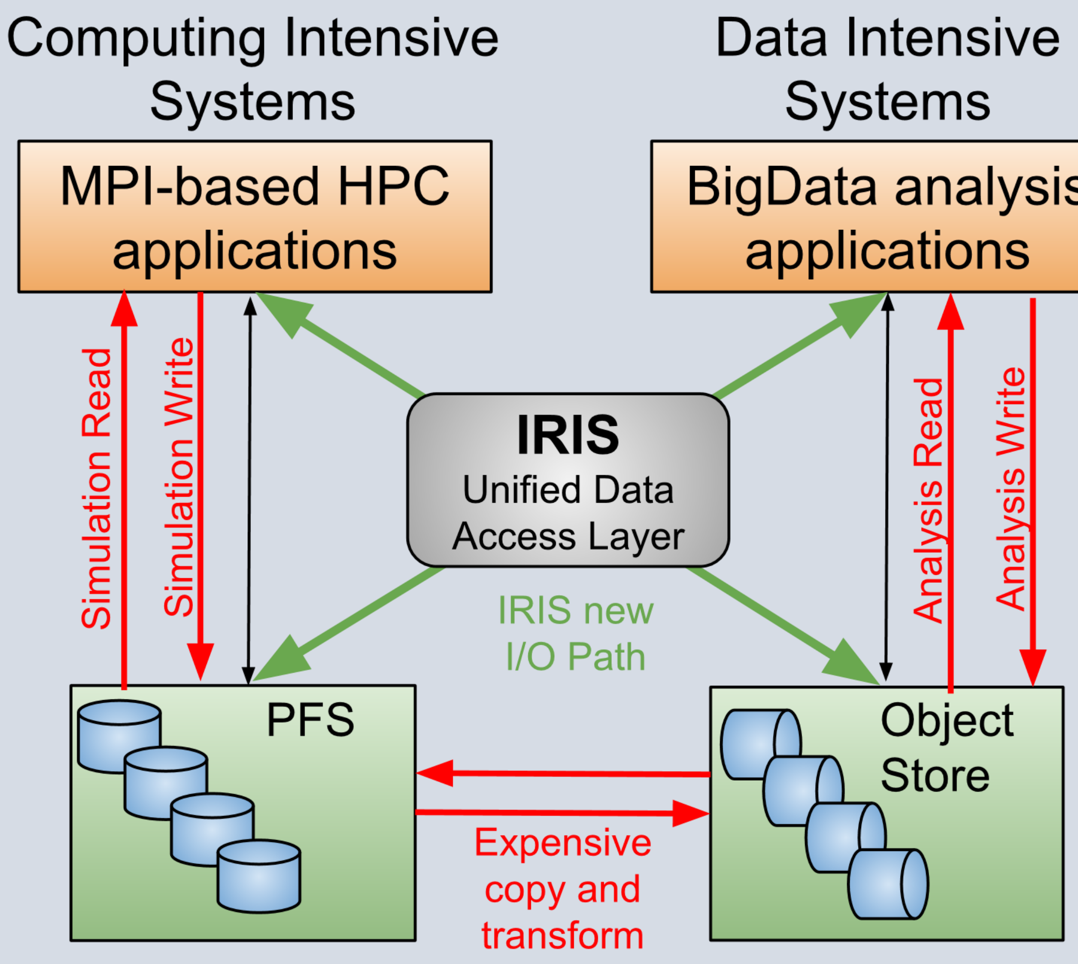
- IRIS strict complies with POSIX standard for maximum compatibility
- IRIS relaxed only maintains metadata relevant to the object mapping
- Relaxed mode offers **18% boost**

IRIS Components Evaluation

- Prefetcher can speed read operations up to **2x**
- POSIX **compliant** in-memory MDM

Workflow Evaluation

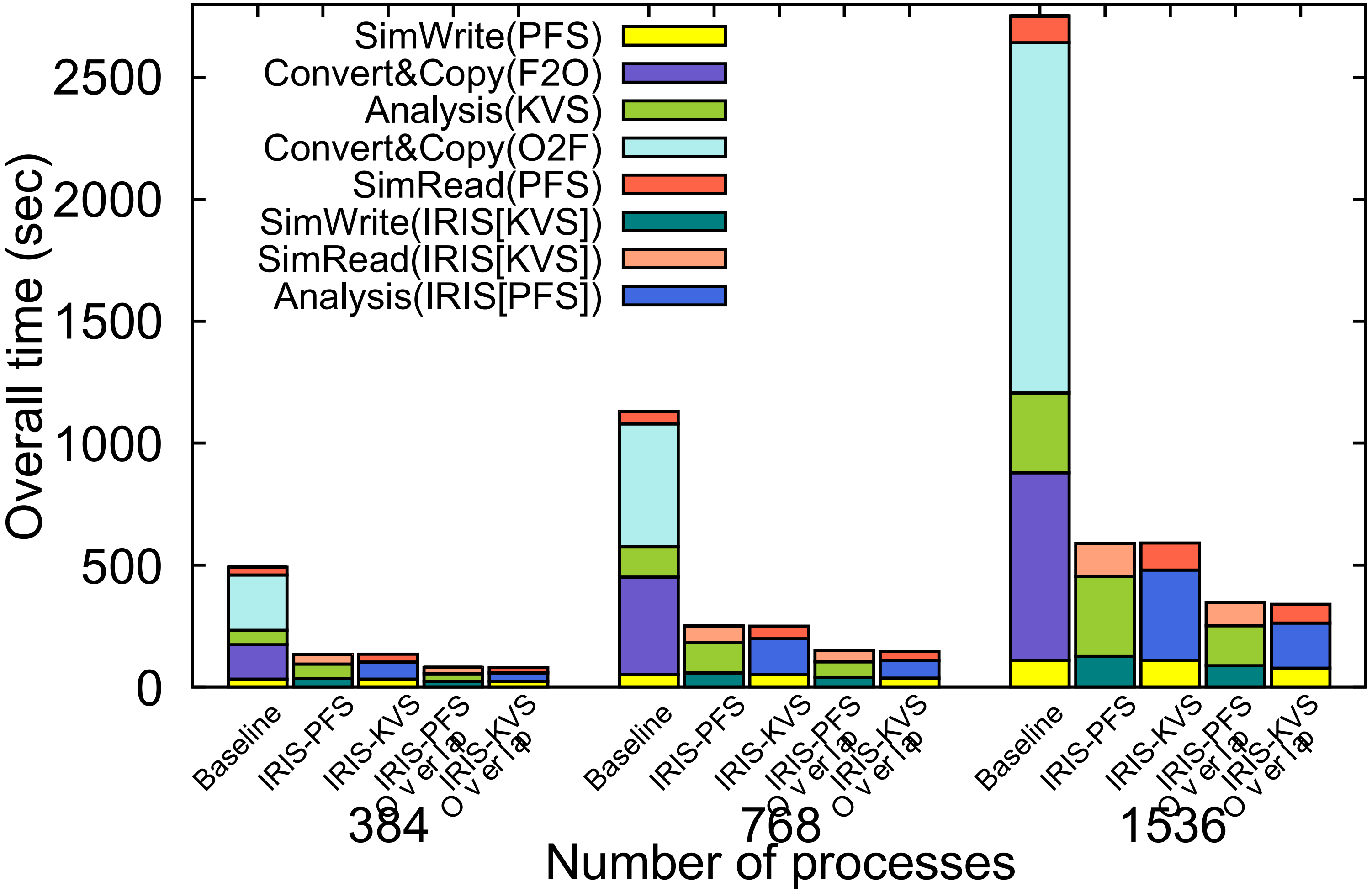
- F2O: copying from PFS to KVS
- O2F: copying from KVS to PFS
- IRIS[PFS]: IRIS operations on top of PFS
- IRIS[KVS]: IRIS operations on top of KVS
- Total time is a compound of several phases.



$$\boldsymbol{Total\ Time} = Simulation\ Write + \text{Copy Data PFS2KVS} + \text{Analysis Read} + \text{Analysis Write} + \text{Copy Data KVS2PFS} + \text{Simulation Read}$$

Real Applications

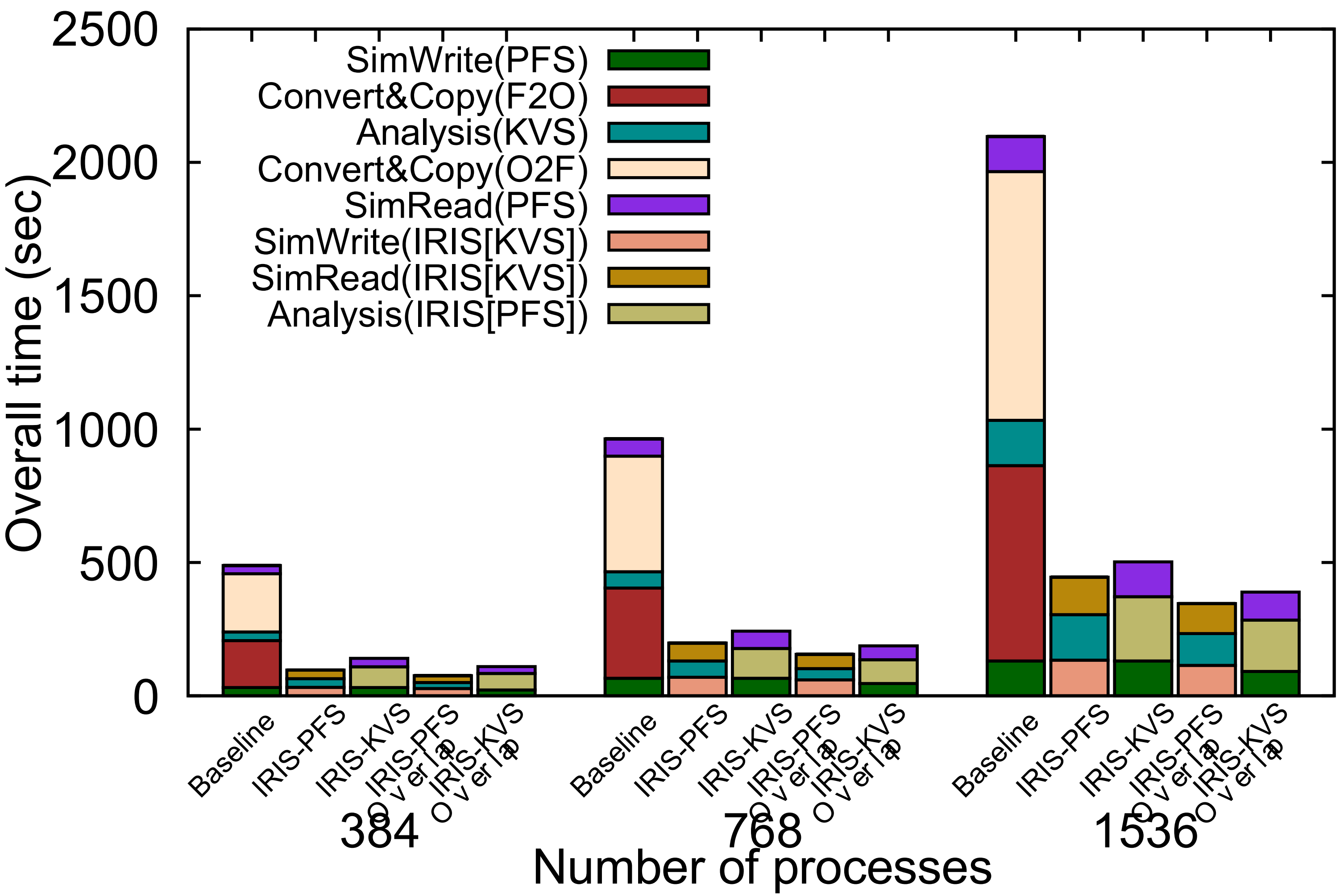
- File-per-process
- Each rank 100MB (150GB total)
- **5x improvement** over baseline
- **7x improvement** overlap mode
- Analysis is 1.7x slower when run on top of PFS
- Copying dominates total time



CM1

Real Applications

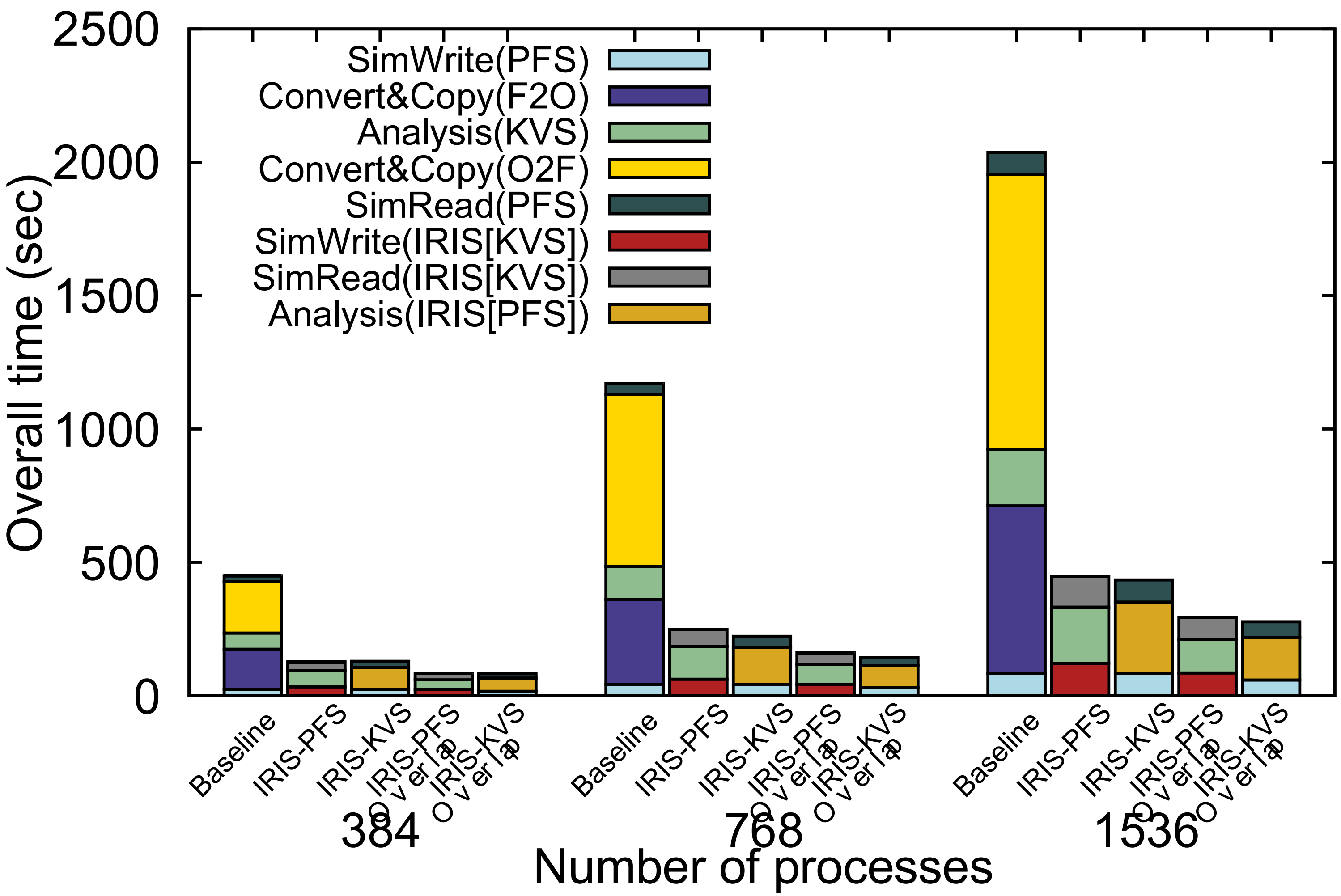
- File-per-process
- Each rank 100MB (150GB total)
- **4x improvement** over baseline
- **6x improvement** overlap mode
- Analysis is 2.2x slower when run on top of PFS



Montage

Real Applications

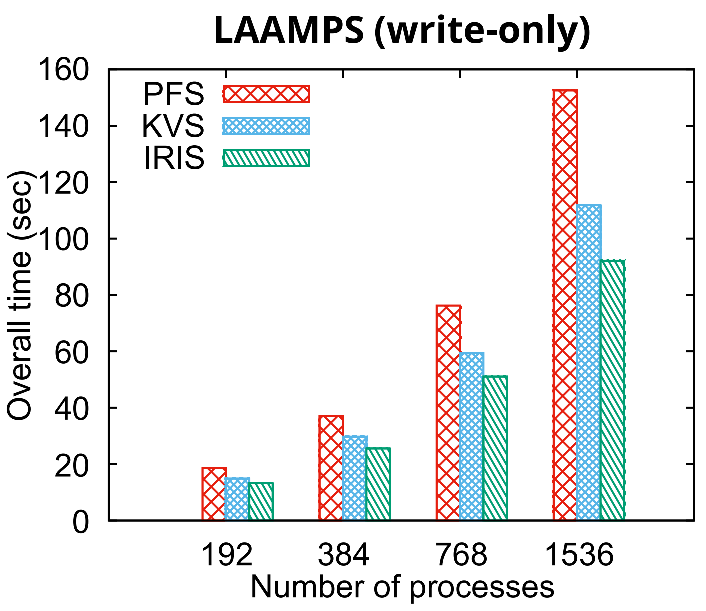
- File-per-process
- Each rank 100MB (150GB total)
- **5x improvement** over baseline
- **7x improvement** overlap mode
- Copying dominates total time
- Analysis is 50% slower when run on top of PFS

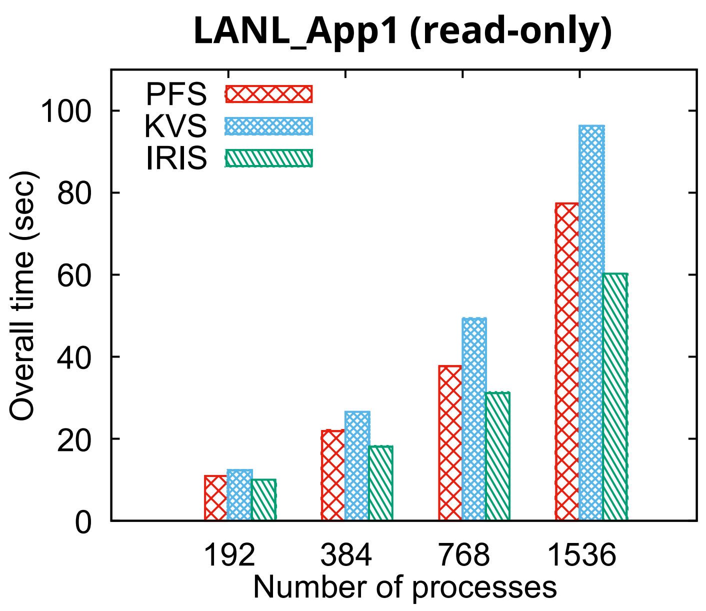


WRF

IRIS in hybrid mode

- Large requests placed in PFS
- Small access directed to KVS
- Each process 32MB total 48GB
- LAMMPS:
  - Threshold: 64KB
  - Ratio small/large requests: 2-to-1
  - Favoring KVS
- LANLApp1:
  - Threshold: 128KB
  - Ratio small/large requests: 1-to-4
  - Favoring PFS





65% improvement over PFS
21% improvement over KVS

28% improvement over PFS
59% improvement over KVS

Related Work

- From the File system side:
  - CephFS
  - PanasasFS
  - OBFS: A File System for Object-based Storage Devices OSD
- From the Object store side:
  - AWS Storage Gateway
  - Azure Files and Azure Disks
  - Google Cloud Storage FUSE

IRIS is a general solution that can bridge any File System with any Object Store and does NOT require change in user code or underlying system deployments.

In summary

- HPC and HPDA infrastructures are converging.
- File-based and Object-based storage solutions:
  - We need to raise the level of abstraction.
- IRIS implements several new algorithms to map files to objects and vice versa.
- IRIS offers:
  - Programming convenience
  - Legacy application support
  - Transparent cross-storage integrated data access
  - Performance improvements up to **7x**

IRIS: I/O Redirection via Integrated Storage

Thank you.

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https://sites.google.com/iit.edu/akougkas

National Science Foundation

WHERE DISCOVERIES BEGIN

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