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Introduction to data management and storage for HPC
part2:
I/O on HPC and parallel FS

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Agenda

- Basic on File System
- Introduction to I/O on HPC
- How to perform I/O on HPC
- Distributed FS & other tricks
- Parallel FS: concepts
- Lustre FS
- Lustre example
- Lustre usage

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Basics on File system

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File System

A file system is a set of methods and data structures used to organize, store, retrieve and manage information in a permanent storage medium, such as a hard disk. Its main purpose is to represent and organize resources storage.

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File System: elements

Name space: is a way to assign names to the items stored and organize them hierarchically.

API: is a set of calls that allow the manipulation of stored items

Security Model: is a scheme to protect, hide and share data.

Implementation: is the code that couples the logical model to the storage medium.

File Systems: Basic Concepts

Disk: A permanent storage medium of a certain size.

Block: The smallest unit writable by a disk or file system. Everything a file system does is composed of operations done on blocks.

Partition: A subset of all the blocks on a disk.

Volume: The term is used to refer to a disk or partition that has been initialized with a file system.

Superblock: The area of a volume where a file system stores its critical data.

File Systems: Basic Concepts (2/2)

Metadata: A general term referring to information that is about something but not directly part of it.

Journaling: write data to journal, commit to file system when complete in atomic operation

- reduces risk of corruption and inconsistency

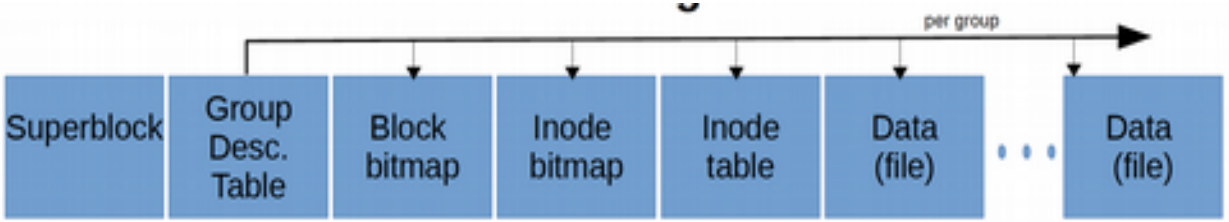
Attribute: A name and value associated with the name. The value may have a defined type (string, integer, etc.).

File Systems: modern concepts

- *Snapshot*: retain status of file system at given point in time by copying metadata and marking object data referred as *copy-on-write*
- *Deduplication*: identify identical storage objects, consolidate and mark them *copy-on-write*

File system : data layout

- How can retrieve data from the disk ?



- Superblock: filesystem type, block counts, inode counts, supported features...
- Group descriptor: location of group data structure, group status
- Group bitmap: one block of 1 bit for allocation status of each blocks
- Inode bitmap: [per group] one block of 1 bit for allocation status of each inode
- Inode Table: [per group] store information of the inode
- Data: your data, finally..

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File system : data layout (2)

```
[root@elcid ~]# tune2fs -l /dev/sda1
tune2fs 1.41.12 (17-May-2010)
Filesystem volume name:   <none>
Last mounted on:          /boot
Filesystem UUID:          72228245-8322-4b2f-b043-317f5d9653df
Filesystem magic number:  0xEF53
Filesystem revision #:    1 (dynamic)
Filesystem features:      has_journal ext_attr resize_inode dir_index filetype
// needs_recovery extent flex_bg sparse_super large_
// file huge_file uninit_bg dir_nlink extra_isize
Filesystem flags:         signed_directory_hash
Default mount options:    user_xattr acl
Filesystem state:         clean
Errors behavior:          Continue
Filesystem OS type:       Linux
Inode count:              38400
Block count:              153600
Reserved block count:     7680
Free blocks:              116833
Free inodes:              38336
First block:              0
Block size:               4096
Fragment size:            4096
Reserved GDT blocks:      37
Blocks per group:         32768 [...]
```

File system : data layout and inode

- Data structure pointed by the inode number, a unique identifier of a file in the file system
  - address of data block on the storage media
  - description of the file (POSIX)
    - Size of the file
    - Storage device ID
    - User ID of the file's owner.
    - Group ID of the file.
    - File type
    - File access right
    - Inode last modification time (ctime)
    - File content last modification time (mtime),
    - Last access time (atime).
    - Count of hard links pointed to the inode.
    - Pointers to the disk blocks that store the file's contents

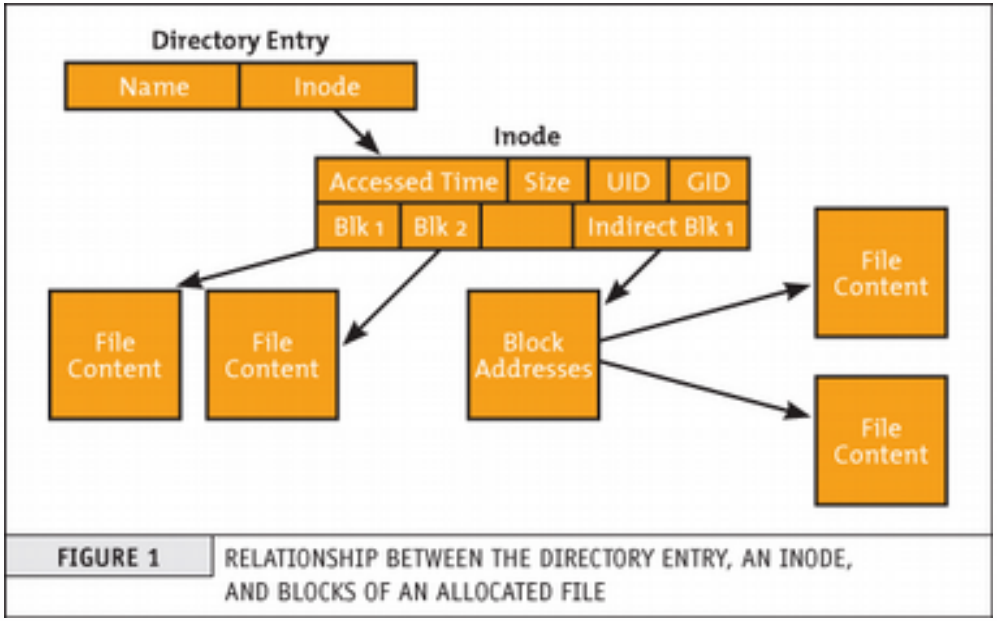

FIGURE 1 RELATIONSHIP BETWEEN THE DIRECTORY ENTRY, AN INODE, AND BLOCKS OF AN ALLOCATED FILE

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F-S useful command to check inodes

- ls -i
- stat filename
- df -i

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Data and metadata

Meta-data : Data to describe data attribute (and extended attribute)

- size, owner, creation date

Meta-data are the bottleneck of scalability

- How many times do you type ls in a day?
  How many times to you write a file?
- ltis scanning all the files in the directory !

(Local) Linux File Systems: few examples

- ext2, ext3, ext4
- Reiserfs
- Xfs
- ...

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Posix

- API to access data and metadata (1988)
- POSIX interface is a useful, ubiquitous interface for building basic I/O tools.
- Standard I/O interface across many platforms.
  - open, read/write, close functions in C/C++/Fortran
- Sequential mode (single stream of accesses)

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Posix API (1/2)

Retrieve the list of all files in a directory: 1 call

`Readdir`

Retrieve the attribute of the all files from this directory:

`Fstat` 1 call per file !

Questions:

What happens if the content of a directory is modified by another process?

Posix API (2/2)

Posi assumes atomicity and ubiquity

Changes are visible immediately to all clients

Problem for parallel accesses:

- POSIX requires a strict consistency to sequential order : lock

  (Create a directory is an atomic operation with immediate global view)
- No support for non-continuous I/O
- No hint / prefetching

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Introducing I/O on HPC

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HPC and I/O

Scientific applications use I/O:

- to store dataset from simulations for later analysis (output)
- to load initial conditions or datasets for processing (input)
- checkpointing to files that save the state of an application in case of system failure
- implement 'out-of-core' techniques for algorithms that process more data than can fit in system memory

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Building block for HPC I/O systems

- A HPC I/O system should:
  - Present storage as a single, logical storage unit
  - Stripe files across disks and nodes for performance
  - Tolerate failures (in conjunction with other HW/SW)
  - Provide a standard interface
- Issues:
  - "Management problem": many disks around our cluster but not easy to make them available to user in a clean/safe/cheap way.
  - "Performance problems" : large dataset requires high performance I/O solutions

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HPC optimization works

- Most optimization work on HPC applications is carried out on:
  - Single node performance
  - Network performance (communication)
  - I/O only when it becomes a real problem

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I/O challenge in HPC

Large parallel machines should perform large calculations

=> Critical to leverage parallelism in all phases including I/O

(do you remember Amdahl law ?)

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Scalability Limitation of I/O

- I/O subsystems are typically very slow compared to other parts of a supercomputer
  - You can easily saturate the bandwidth
- Once the bandwidth is saturated scaling in I/O stops
  - Adding more compute nodes increases aggregate memory bandwidth and flops/s, but not I/O

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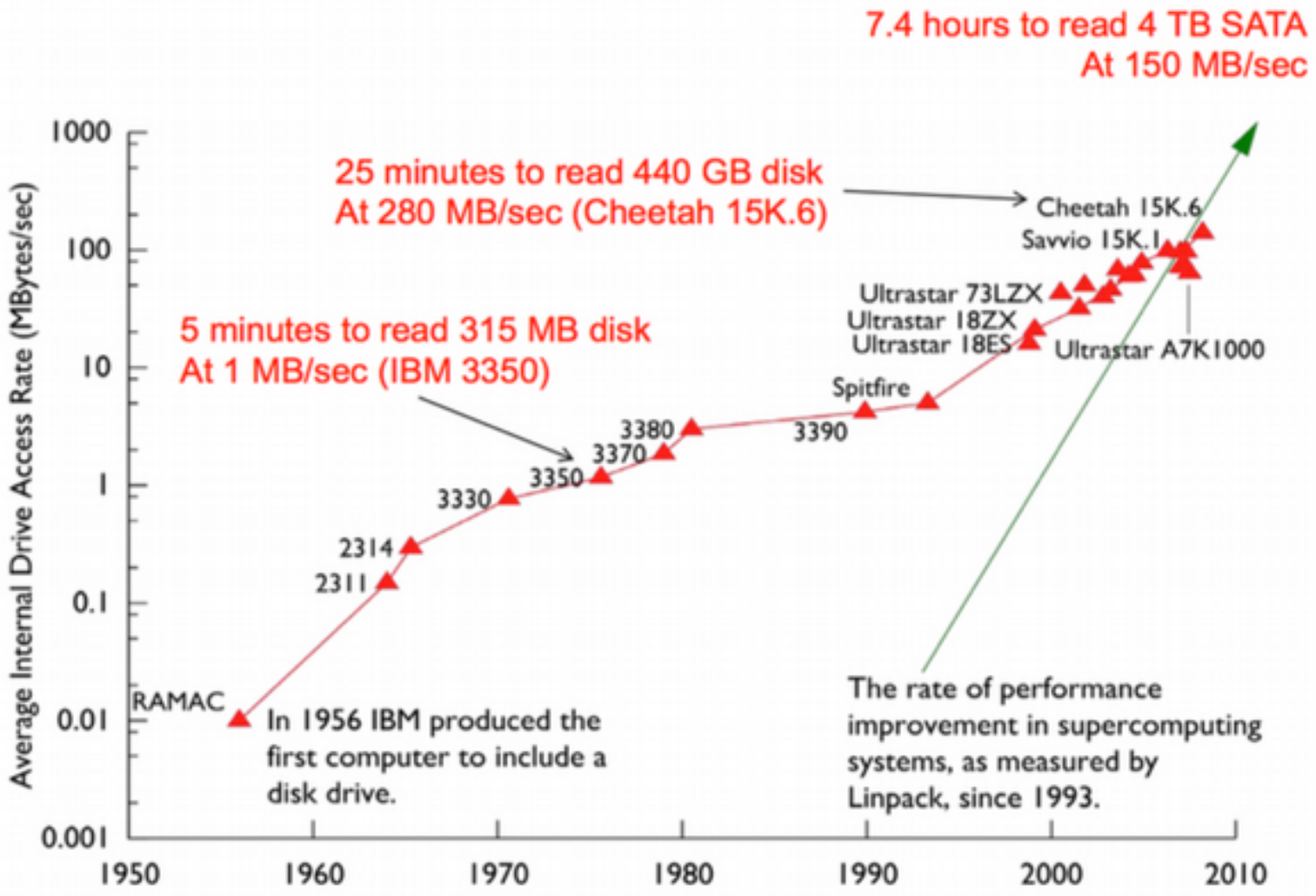

Figure by Rob Ross, Argonne National Laboratory

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Factors which affect I/O

- How is I/O performed?
  - I/O Pattern
  - Number of processes and files.
  - Characteristics of file access.
- Where is I/O performed?
  - Characteristics of the computational system.
  - Characteristics of the file system.

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HOW TO PERFORM I/O on HPC

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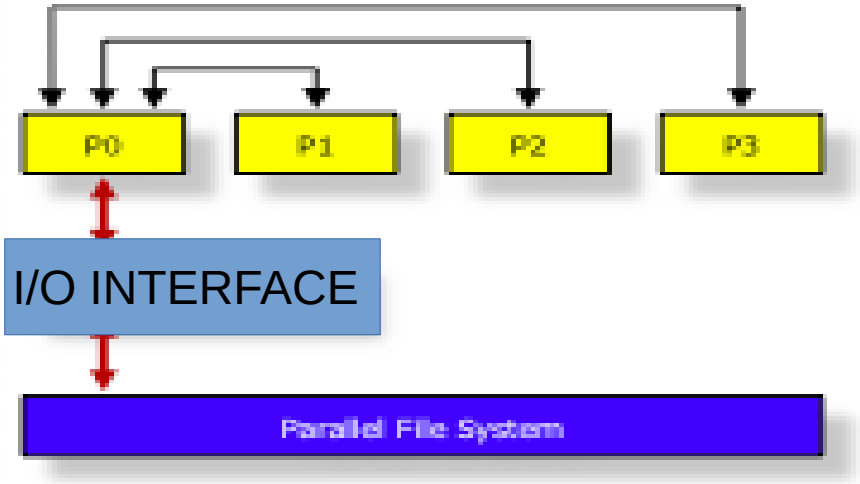
Serial I/O : spokeperson

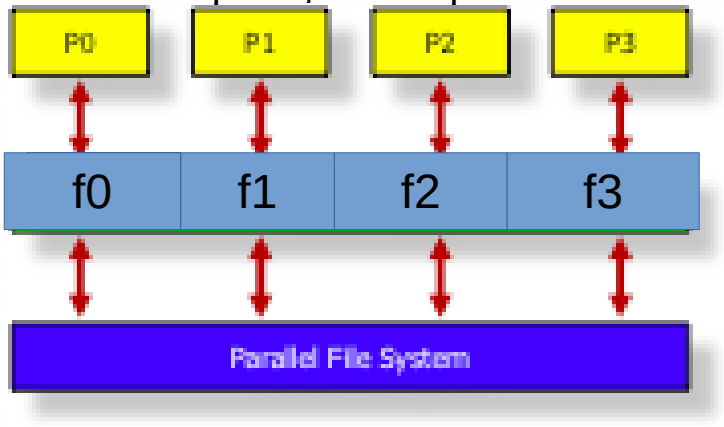
- One process performs I/O.
  - Data Aggregation or Duplication
  - Limited by single I/O process.
- Simple solution, easy to manage, but Pattern does not scale.
  - Time increases linearly with amount of data.
  - Time increases with number of processes.



Parallel I/O: File-per-Process

All processes perform I/O to individual files.

- Limited by file system.
  - Pattern does not scale at large number of processes
    - Number of files creates bottleneck with metadata operations.
    - Number of simultaneous disk accesses creates contention for file system resources.
- Manageability issues:
    - What about managing thousand of files ???
    - What about checkpoint/restart procedures on different number of processors ?



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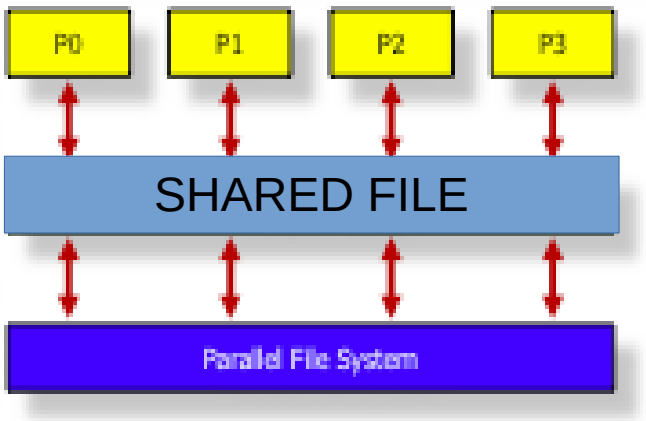
Parallel I/O

- Each process performs I/O to a single file which is shared.
- Performance Data layout within the shared file is very important.
- Possible contention for file system resources when large number of processors involved..



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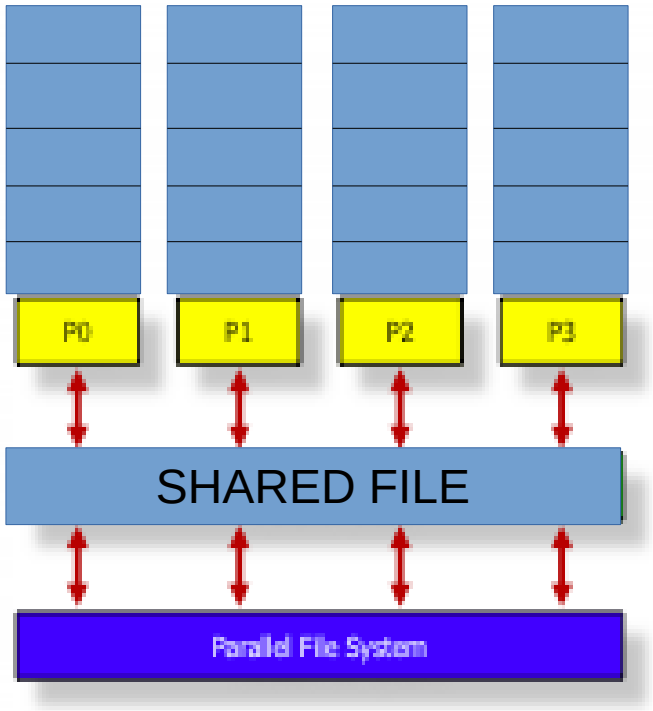
Parallel I/O on very large system..

- Accessing a shared filesystem from large numbers of processes could potentially overwhelm the storage system and not only..
- In some cases we simply need to reduce the number of processes accessing the storage system in order to match number of servers or limit concurrent access.



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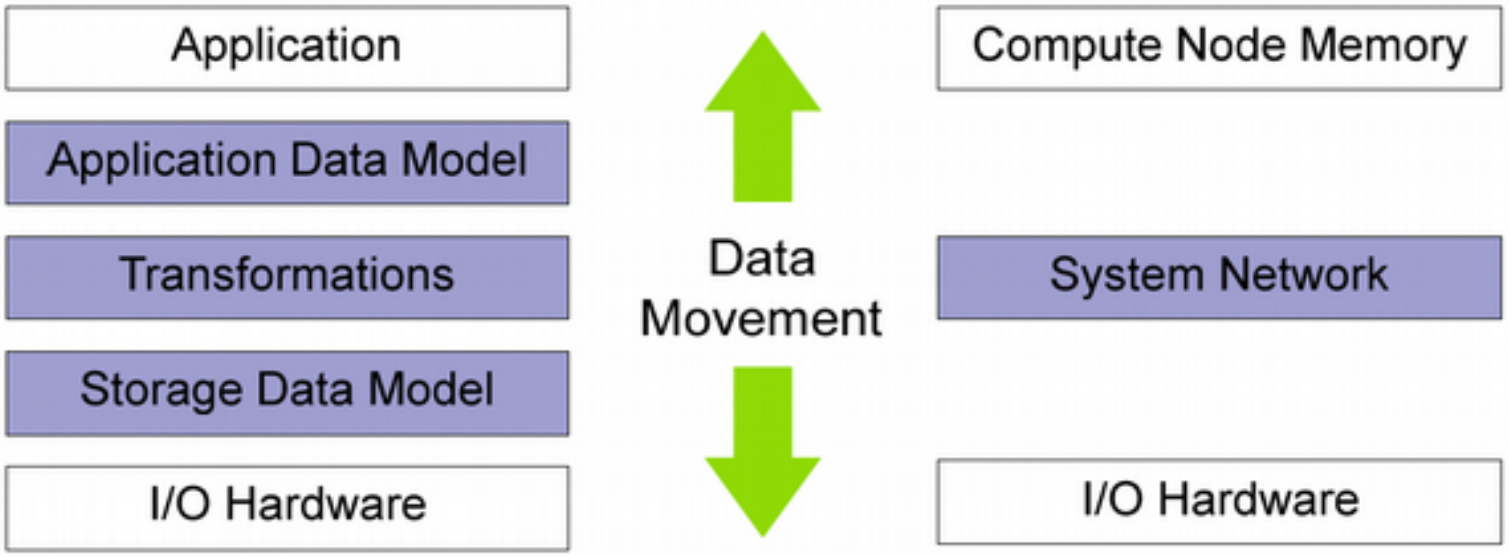
Views of data access on HPC systems

- Logical vs Physical View



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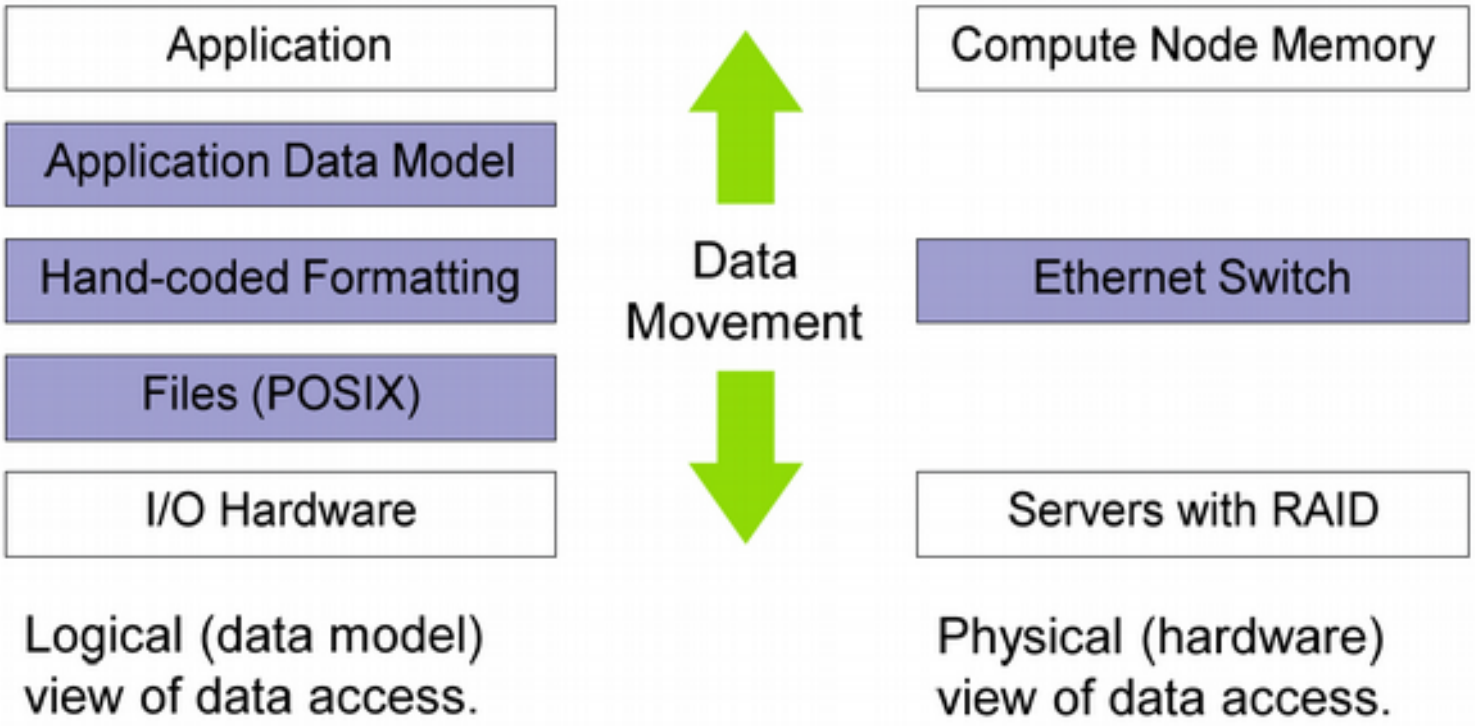
Data access in old HPC systems..

Applications teams wrote their own translation from their data model to files.



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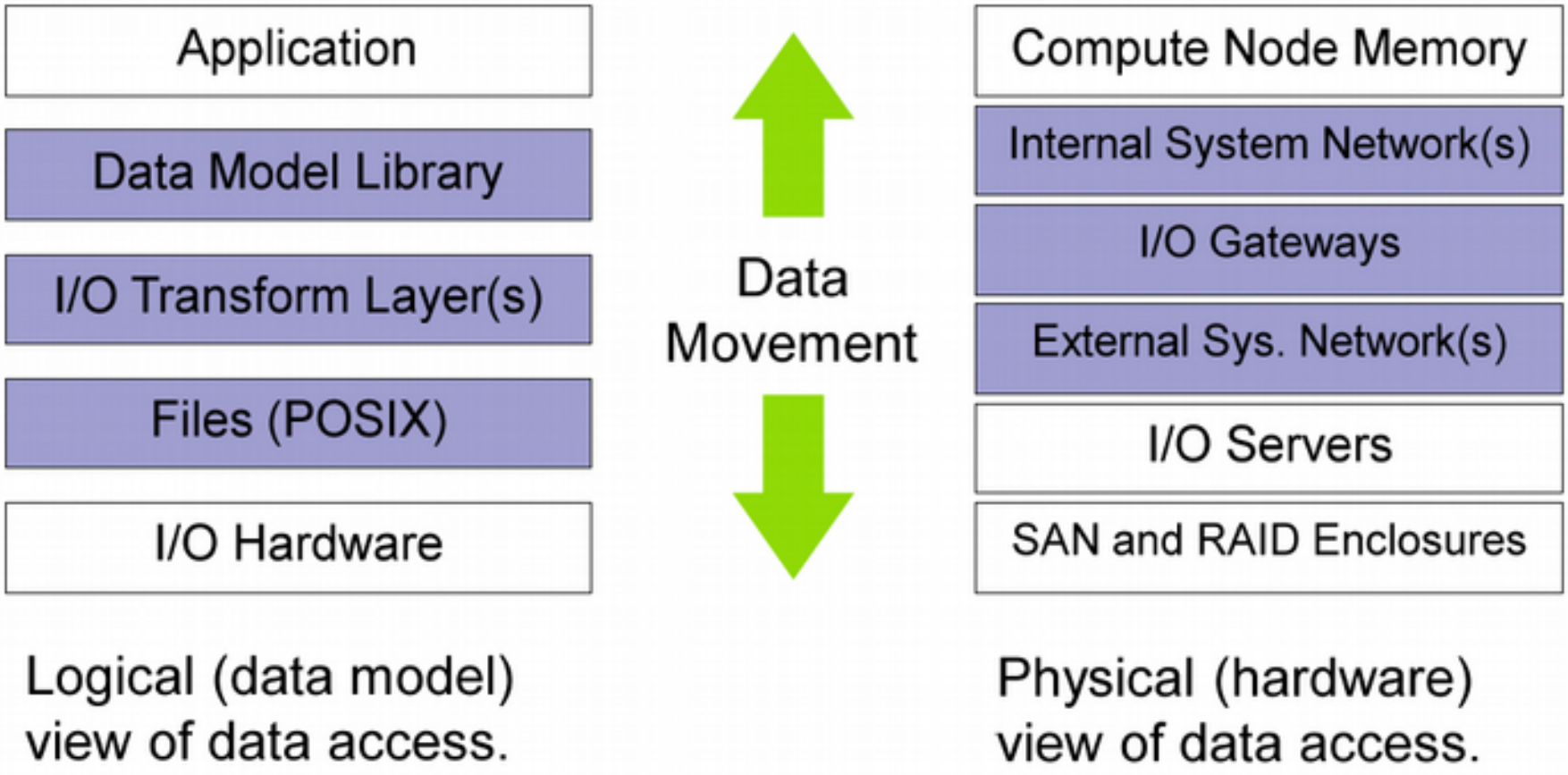
Data access in current HPC systems..

Greater /extended support on logical side, much more complexity on Hardware side



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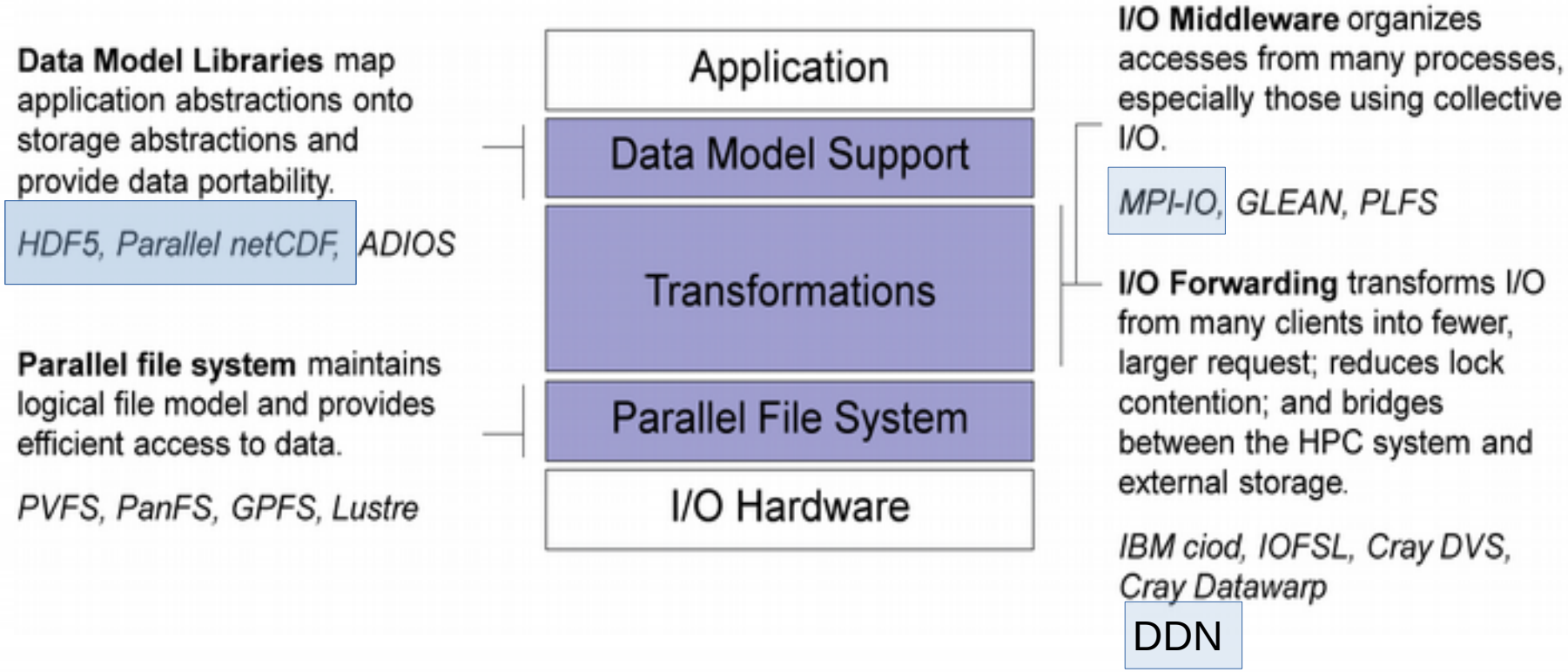
HPC I/O software stack



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I/O middleware

- Match the programming model (e.g. MPI)
- Facilitate concurrent access by groups of processes
  - Collective I/O
  - Atomicity rules
- Expose a generic interface
  - Good building block for high-level libraries
- Efficiently map middleware operations into PFS ones
  - Leverage any rich PFS access constructs, such as
    - Scalable file name resolution
    - Rich I/O descriptions

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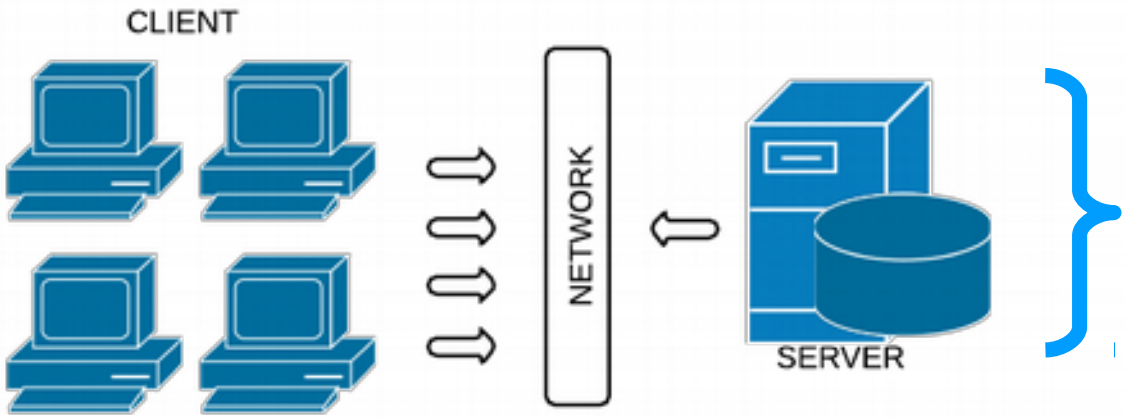
Distributed file system

- FS hosted on a server (I/O server)
  - Mounted by several clients (compute nodes/login nodes..)
  - Example: NFS
    - Parallel acces is possible but:
    - Network bandwith limited..
    - Locking issues



SPOF!
bottleneck!

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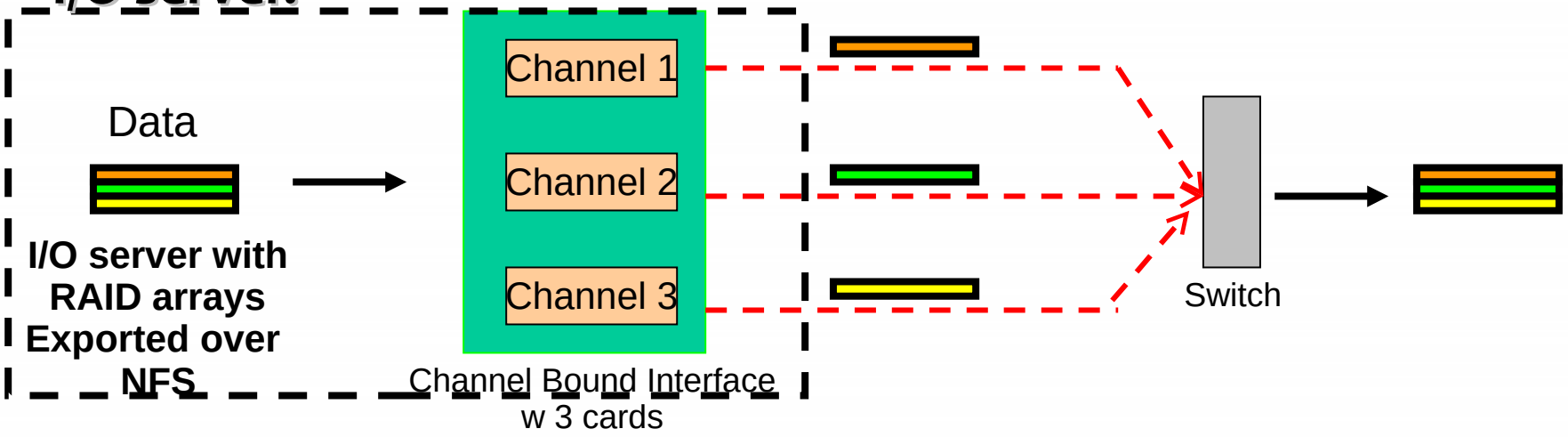
I/O server.



I/O performance can be obtained/ increased by combing RAID (for I/O and/or security and channel bonding (for increased bandwidth).

Good: cheap and easy to maintain and configure.

Bad:

- performance is marginal (N disks give N I/O speedup at best), .
- Need a high end network switch.
- Performance degrades fast as the function of the number of users.
- Needs lots of memory on I/O server to allow for good buffering.
- Needs good UPS/Shutdown solution, to prevent disk corruption.

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PFS for HPC

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Parallel FS solution

- A parallel solution usually is made of
  - several Storage Servers that hold the actual filesystem data
  - one or more Metadata Servers that help clients to make sense of data stored in the file system
- and optionally:
  - monitoring software that ensures continuous availability of all needed components
  - a redundancy layer that replicates in some way information in the storage cluster, so that the file system can survive the loss of some component server

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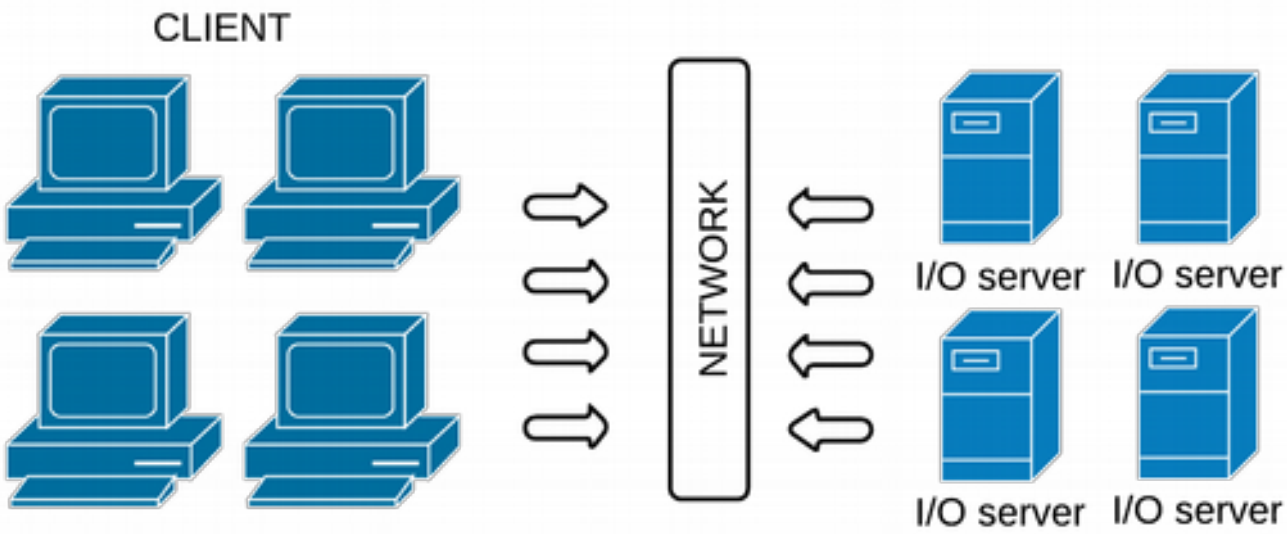
Parallel File System: Typical configuration



1) Each I/O server hosts some data
2) Metadata server coordinates access by the clients to the data
3) Metadata server hosted on I/O server (dedicated and/ or shared)

Parallel filesystem approach

- In a parallel solution..
  - you add storage servers, not only disk space
  - each added storage server brings in more memory, more processor power, more bandwidth
  - software complexity however is much higher
- there is no «easy» solution, like NFS...

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A disclaimer...

- Parallel File Systems are usually optimized for high performance rather than general purpose use,
- Otimization criteria:
  - –Large block sizes (≥ 64kB)
  - –Relatively slow metadata operations (eg. fstat()) compared to reads and writes..
  - –Special APIs for direct access and additional optimizations

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Hardware to build a PFS

- Disks, controllers, and interconnects
- Hardware defines the peak performance of the I/O system:
  - raw bandwidth
  - Minimum latency
- At the hardware level, data is accessed at the granularity of blocks, either physical disk blocks or logical blocks spread across multiple physical devices such as in a RAID array
- Parallel File Systems takes care of
  - managing data on the storage hardware,
  - presenting this data as a directory hierarchy,
  - coordinating access to files and directories in a consistent manner

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What is available on the market ?

- BeeGFS/FHGFS
  - Developed at Fraunhofer Institute, freely available not open
  - http://www.fhgfs.com/cms/

  Lustre
  - open and Free owned by ~~Intel~~ DDN
  - Intel no longer sells tool to manage and support ($$$)
  - http://lustre.opensfs.org/
- GPFS
  - IBM proprietary $$$
  - http://www-03.ibm.com/systems/platformcomputing/products/gpfs/

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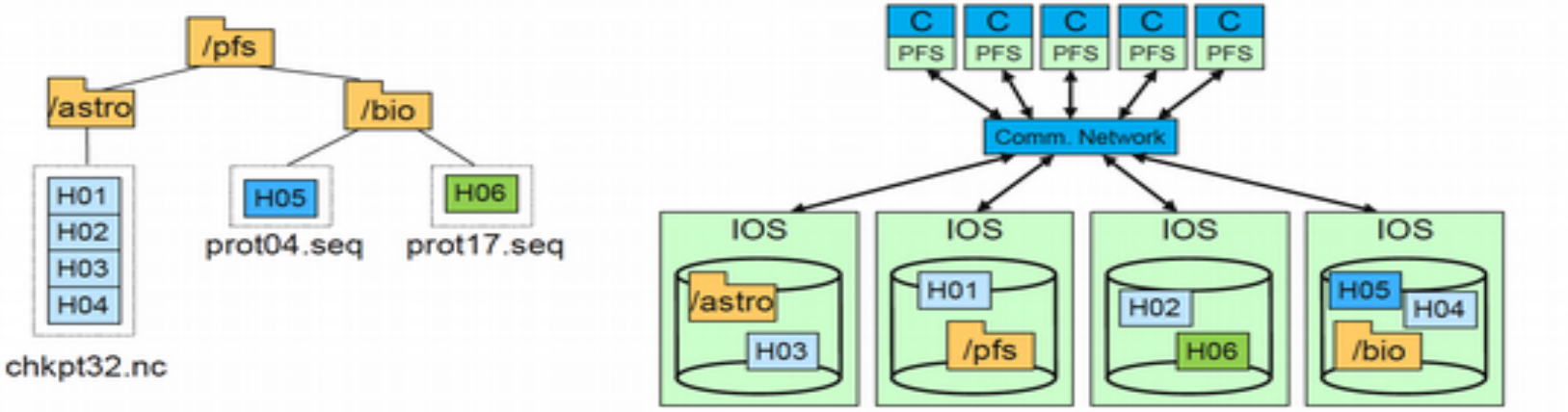
Parallel FS



An example parallel file system, with large astrophysics checkpoints distributed across multiple I/O servers (IOS) while small bioinformatics files are each stored on a single IOS

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Comparing parallel FS

- Block Management
- How Metadata is stored
- What is cached and where
- Fault tolerance mechanisms
- Management/Administration

- Performance
- Reliability
- Manageability
- Cost

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Recap on Metadata

- Metadata names files and describes where they are located in the distributed system
  - Inodes hold attributes and point to data blocks
  - Directories map names to inodes
- Metadata updates can create performance problems
- Different approaches to metadata are illustrated via the File Create operation

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Create a file on local FS

- 4 logical I/Os
  - Journal update
  - Inode allocation
  - Directory insert
  - Inode update
- Performance determined by journal updates
  - Details vary among systems

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Create a file on NFS

- RPC (remote procedure call)
  - Client to NFS server RPC
- NVRAM update (or other trick to)
  - Mirrored copy on peer via RDMA
- Reply to client
- Local I/O
  - Inode alloc, Inode update, Directory
  - Done in the background
- Performance from
  - NVRAM+RDMA

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Create a FS on Lustre

- Client to Server RPC
- Server creates local file to store metadata
  - Journal update, local disk I/O
- Server creates container object(s)
  - Object create transaction with OSS
  - OSS creates local file for object
- Performance dependent on
  - Local file systems on metadata server and OSS/OST

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Lustre FS

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Building blocks of Lustre FS

- Lustre Clients
  - – Remote clients that can mount the Lustre filesystem, e.g. your Linux cluster Compute nodes.
- Object Storage Targets (OST)
  - These are block devices that data will be distributed over. These are commonly RAID6 arrays of HDDs.
- Object Storage Server (OSS)
  - A dedicated server that is directly connected to one or more OSS. These are usually connected to the HPC facility by means via a high performance Network (infiniband)
- MetaData Server (MDS) – A single server per file system that is responsible for holding meta data on individual files
  - Filename and location
  - Permissions and access control
  - Which OSTs data is held on.
- MetaData Target (MDT)
  - block device where medata are physically stored

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Lustre Principles

- Lustre is centralized
  - No copy of data or metadata.
  - Metadata stored on a shared storage called Metadata Target (MDT)
  - Attached to two Metadata Servers (MDS)
- MDS provides the illusion of shared name space
- Lustre is an overlay file system
- Data are stored on back-end file-systems: Object Storage Target (OST)
  - Attached to several Object Storage Servers (OSS) for active/active failover.
  - OSS are the servers that handle I/O requests.

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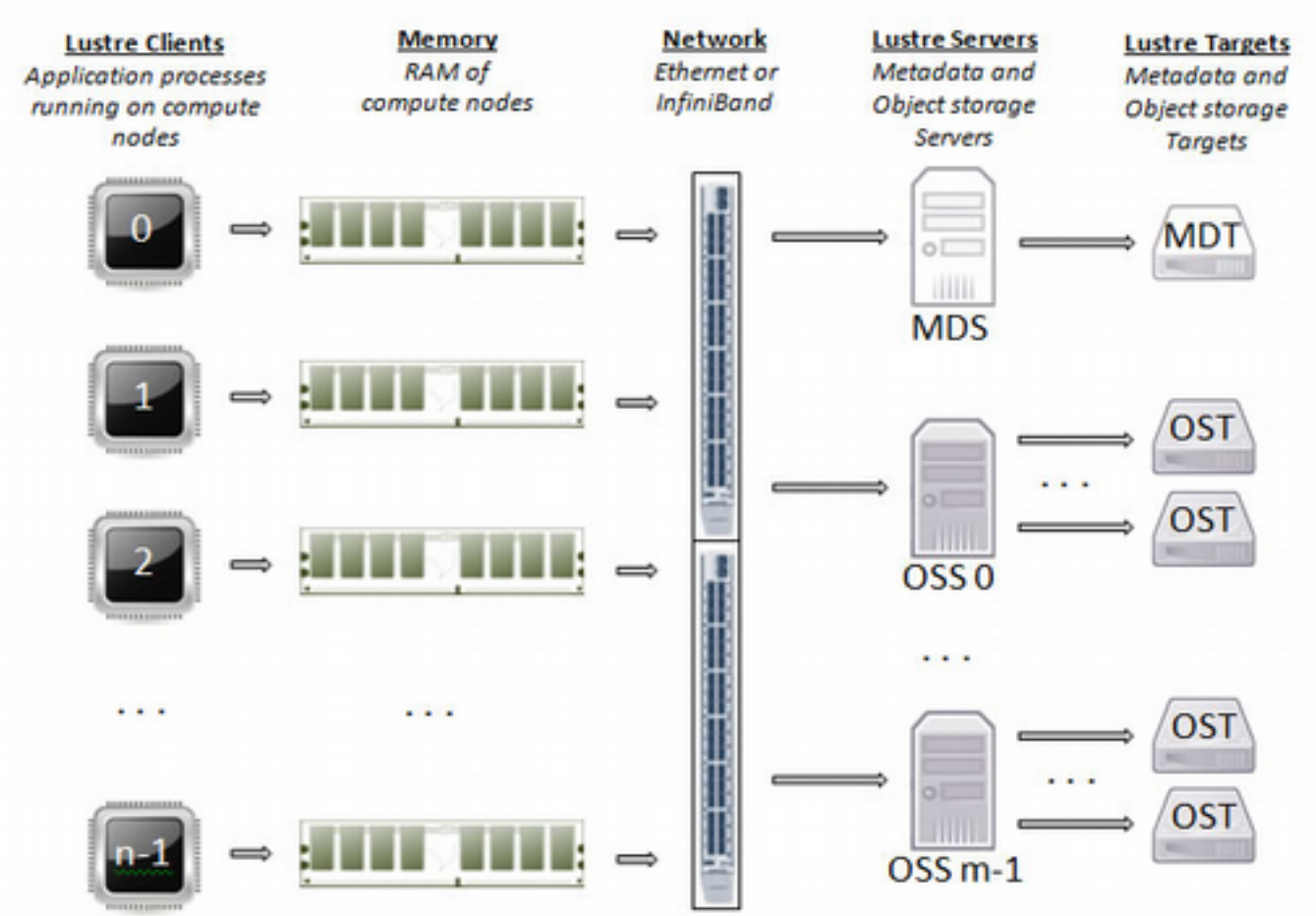
Lustre components



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Lustre component characteristics

- Clients
  - 1 - 100,000 per system
  - Data bandwidth up to few GB/s; 1000's of metadata ops/s
  - No particular hardware or attached storage characteristics required
- Object Storage Servers (OSS)
  - 1 - 1000 per system
  - 500 MB/s..2.5 GB/s I/O bandwidth
  - Require good network bandwidth and adequate local storage capacity coupled with sufficient number of OSSs in the system
- Metadata Servers (MDS)
  - 2 (for redundancy) per system
  - 3,000 - 15,000 metadata ops/s
  - Utilize 1 – 2% of total file system capacity
  - Require memory-rich nodes with lots of CPU processing power

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Lustre Example

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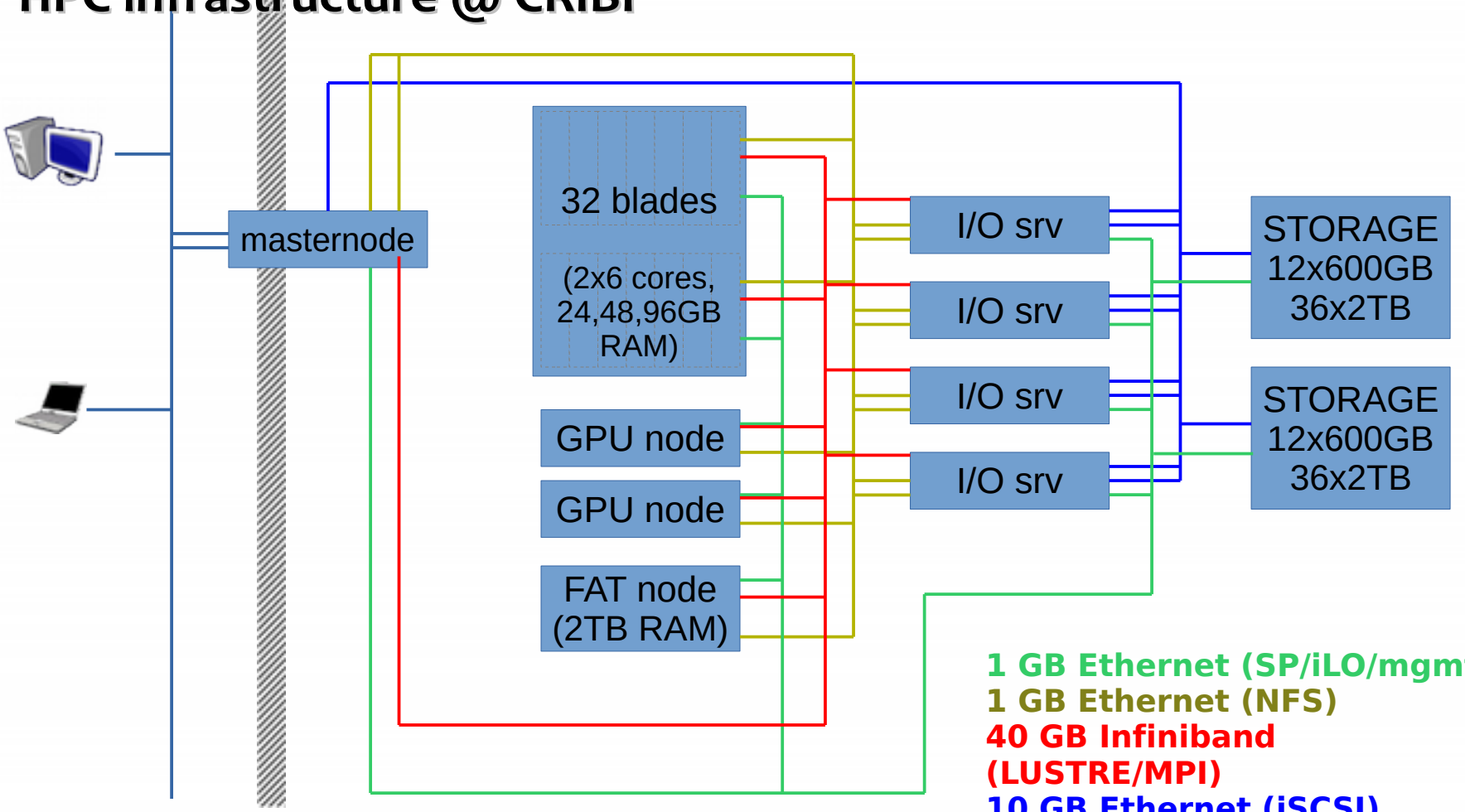
HPC infrastructure @ CRIBI



1 GB Ethernet (SP/iLO/mgmt)
1 GB Ethernet (NFS)
40 GB Infiniband (LUSTRE/MPI)
10 GB Ethernet (iSCSI)
1 GB (LAN)

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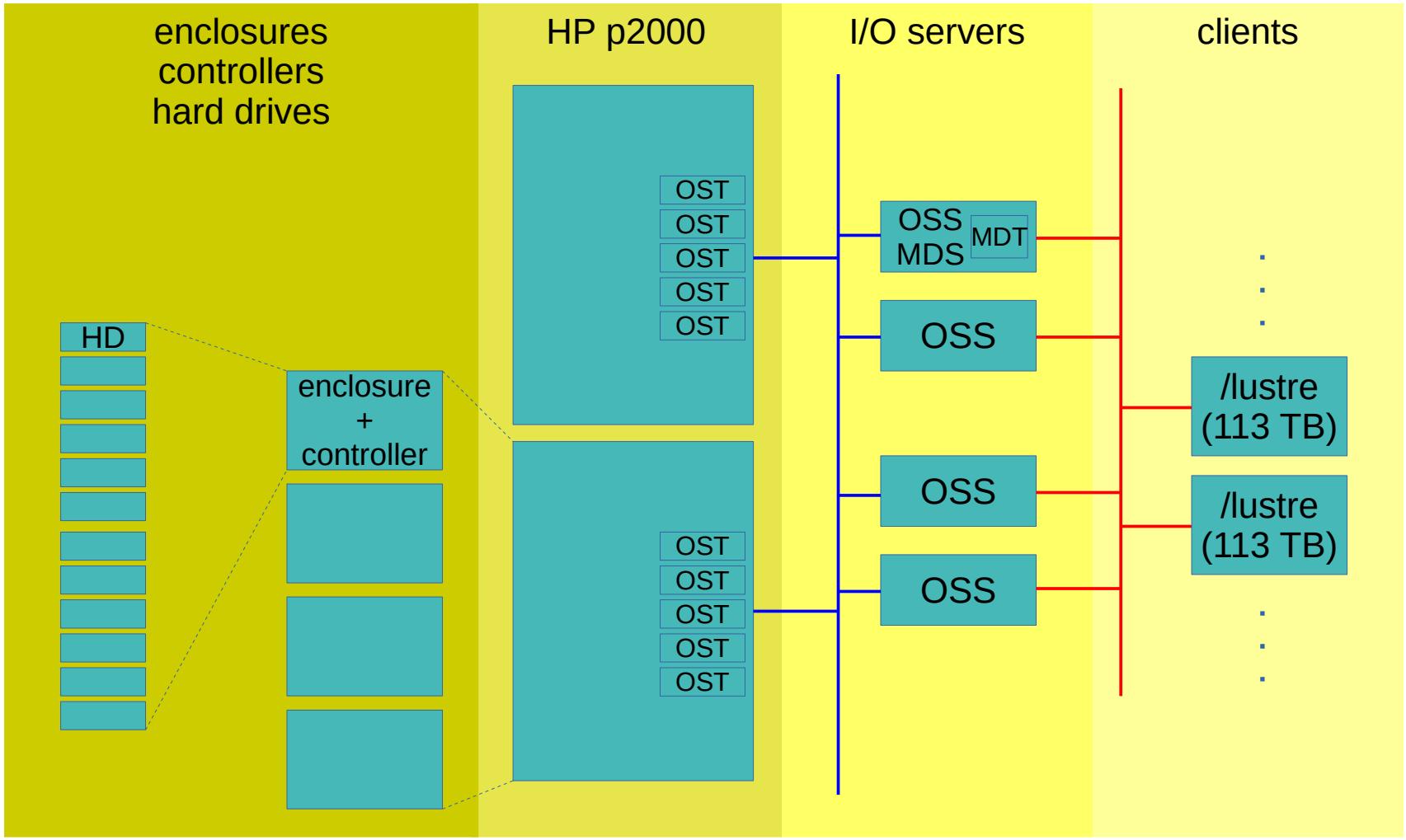
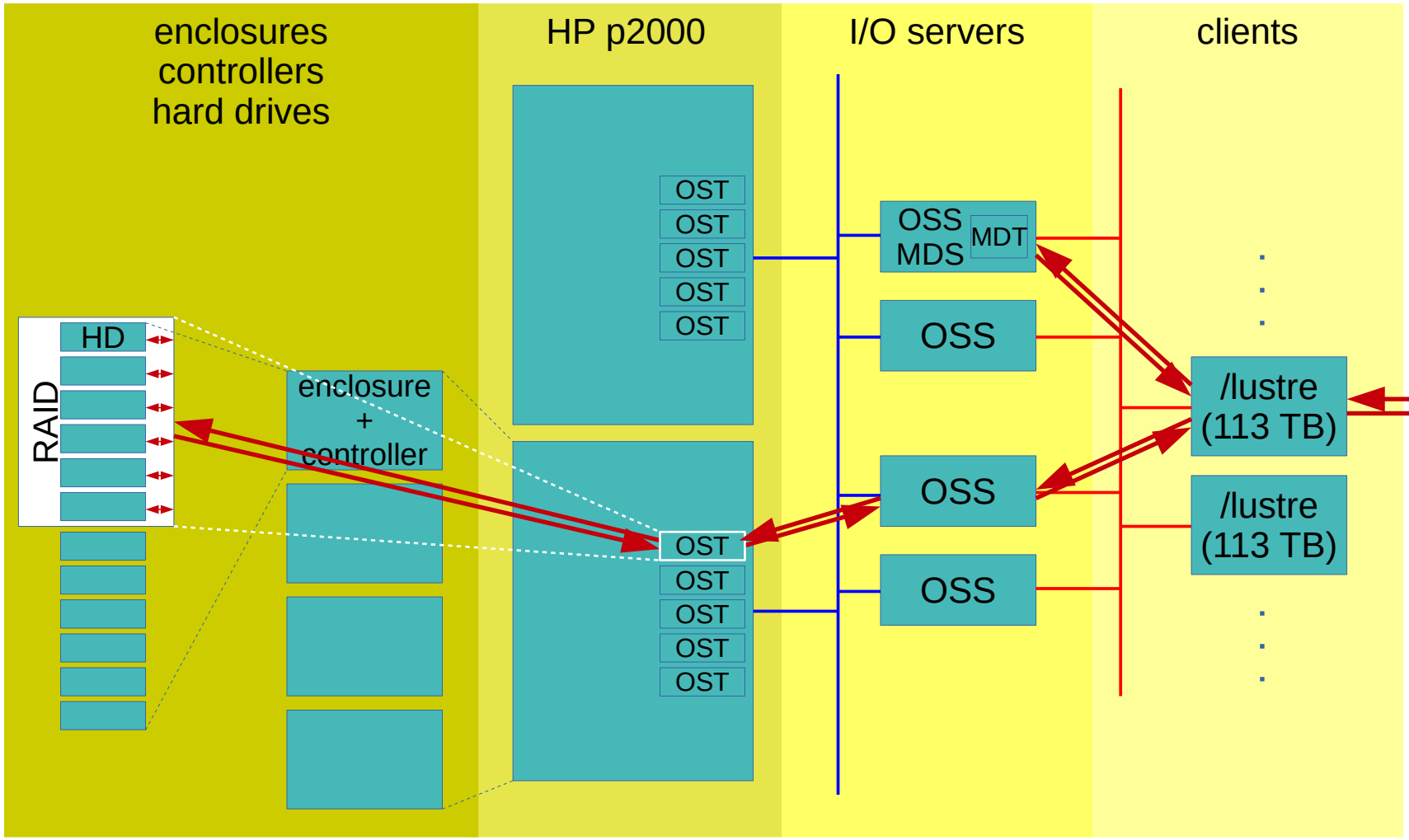
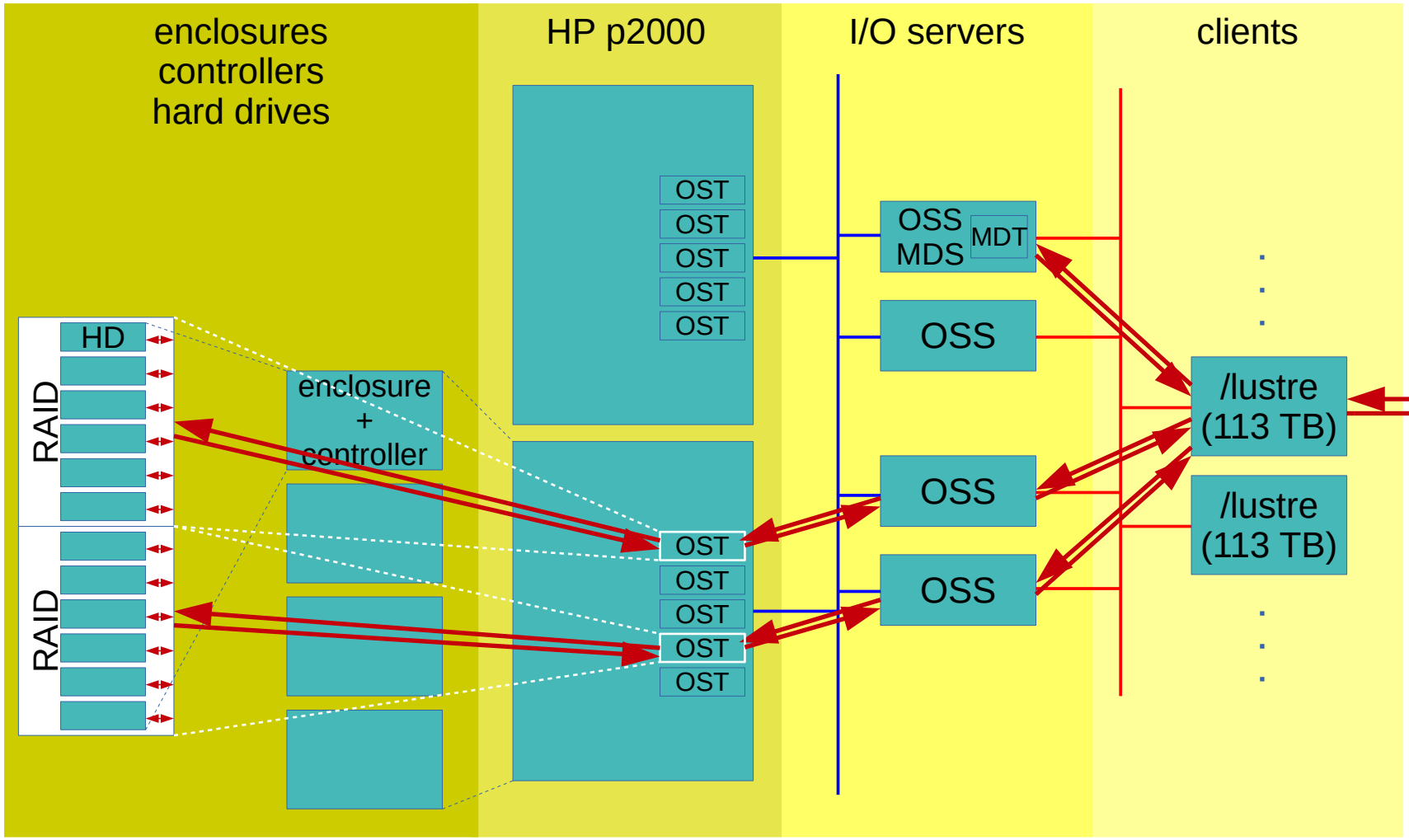
LUSTRE and storage solution



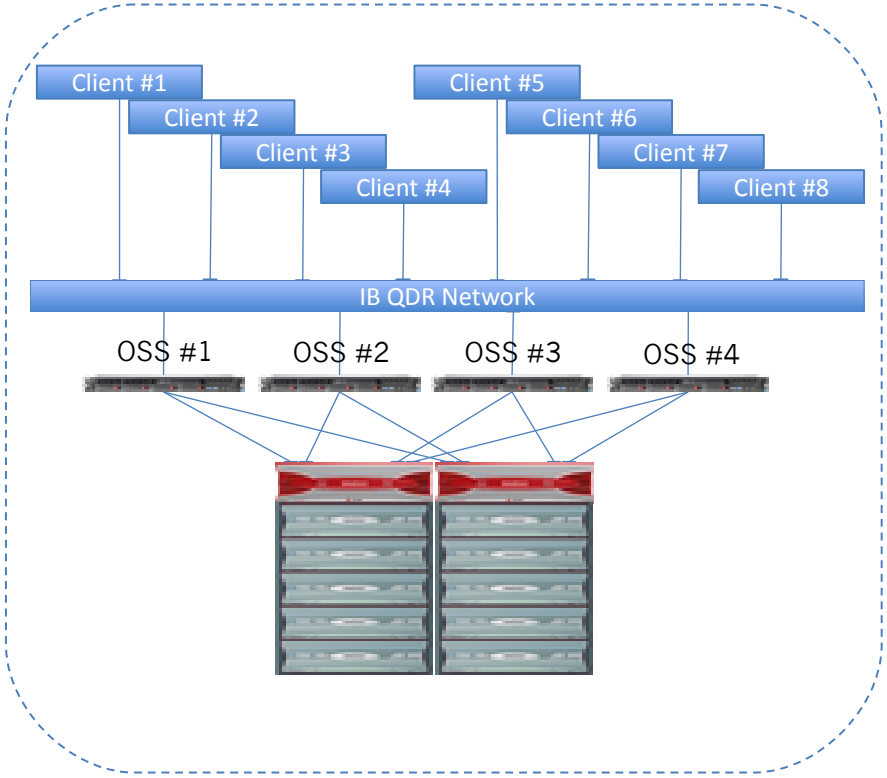
accessing LUSTRE filesystem



why "parallel" filesystem?



overall LUSTRE performance

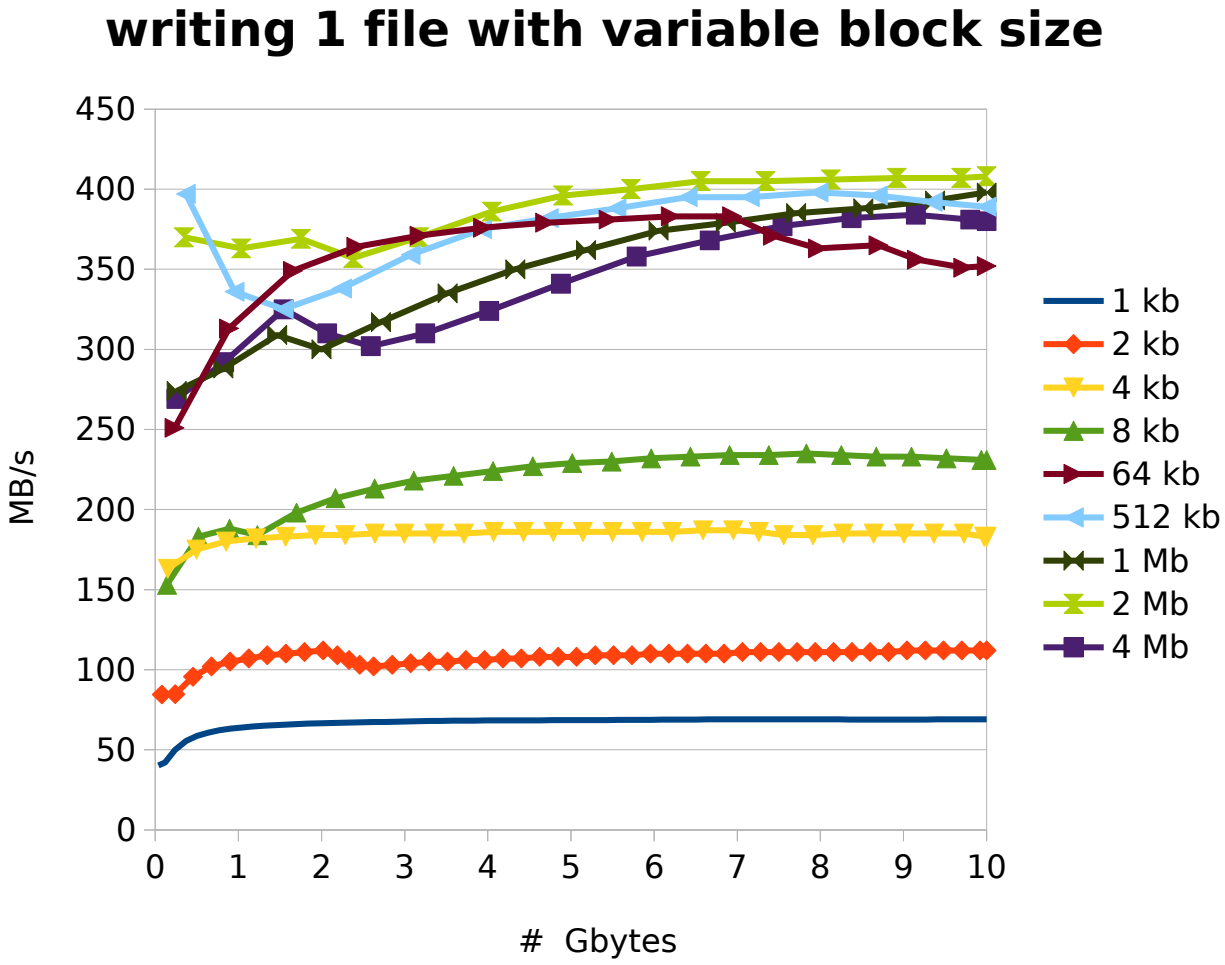


- sequential write/read by iozone
- 1 ~ 8 clients, 1 ~ 4 proc/client
- 32 GB files writing
- 64 GB files reading

~ 1.7 GB/sec writing
32 clients, 32 GB files

~ 1.2 GB/sec reading
32 clients, 64 GB files

LUSTRE can be disappointing too...



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Using Lustre

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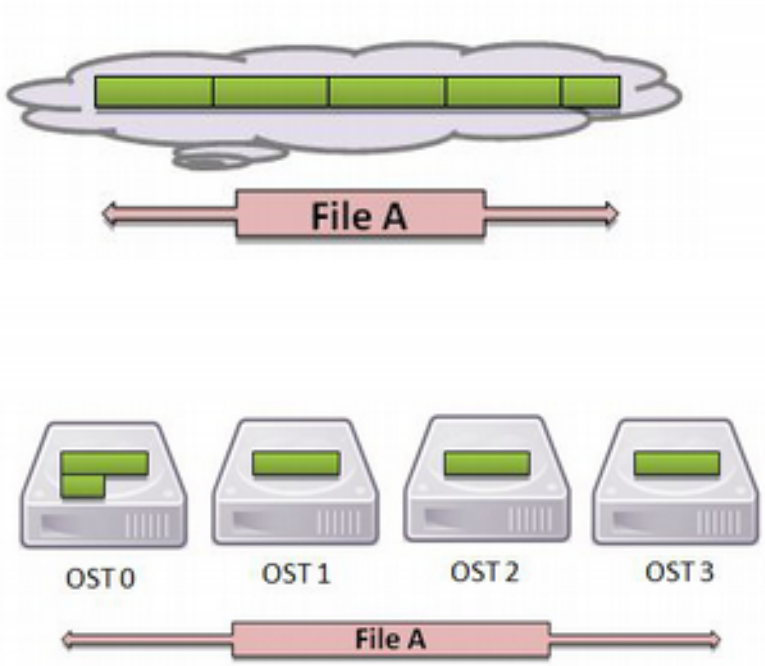
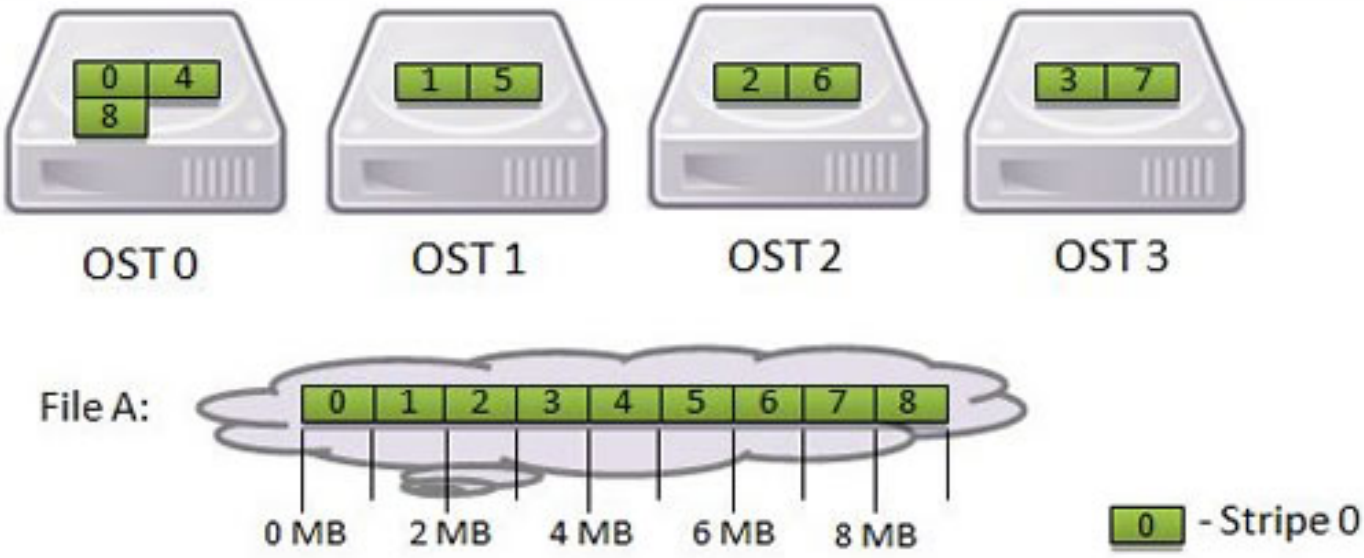
file striping in lustre

- Distribute a file over several OST..



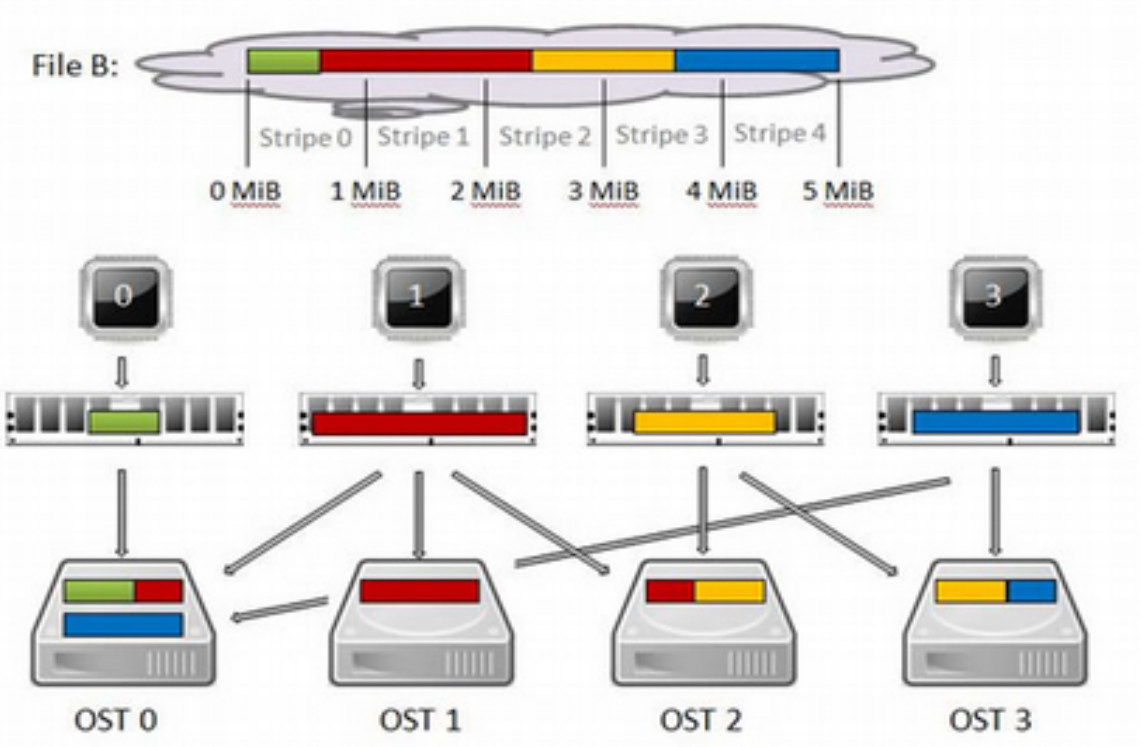
Aligned stripes

- A file large 9Mb
- Stripe size: 1Mb
- Four OST to stripe:



Non aligned stripes

- A file B 5Mb
- Written in parallel with different offset:



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Basic Lustre User command

- Lustre's lfs utility provides several options for monitoring and configuring your Lustre environment.
- You can:
  - List OSTs in the File System
  - Search the Directory Tree
  - Check Disk Space Usage
  - Get Striping Information
  - Set Striping Patterns

```
>lfs -help
```

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lfs basic usage

- `lfs df [-h] [-i]`
  - To check size and number of inodes [-i]

```
[root@m001 ~]# lfs df
UUID                   1K-blocks        Used   Available Use% Mounted on
lustre-MDT0000_UUID    157258928      494864   156764064   0% /lustre[MDT:0]
lustre-OST0000_UUID   6266049040    27197816  6238851144   0% /lustre[OST:0]
lustre-OST0001_UUID   6266049040    26622240  6239425692   0% /lustre[OST:1]
lustre-OST0002_UUID   6266049040    27687756  6238357652   0% /lustre[OST:2]
lustre-OST0003_UUID   6266049040    27897188  6238150736   0% /lustre[OST:3]

filesystem summary:  25064196160   109405000 24954785224   0% /lustre
```

- `lfs quota -u username /your_lustreFS`

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lfs command..

- `lfs osts`
  - Show available OST on filesystem
- `lfs find`

```
[root@m001 ~]# lfs find  /lustre -mtime +30 -type f -print --maxdepth 1
/lustre/wrf-benchmark.tgz
/lustre/pio.tgz
/lustre/wrf-crma-tests.tgz
```

- `lfs getstripe <directory|filename>`
  - Give you info about striping
- `lfs setstripe`
  - Allow you to set the striping

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lfs getstripe.

```
[cozzini@elcid cozzini]$ lfs help getstripe
getstripe: To list the striping info for a given file or files in a
directory or recursively for all files in a directory tree.
usage: getstripe [--ost|-O <uuid>] [--quiet | -q] [--verbose | -v]
                 [--stripe-count|-c] [--stripe-index|-i]
                 [--pool|-p] [--stripe-size|-S] [--directory|-d]
                 [--mdt-index|-M] [--recursive|-r] [--raw|-R]
                 <directory|filename> ...
```

```
[cozzini@elcid cozzini]$ lfs getstripe datafile
datafile
lmm_stripe_count:   1
lmm_stripe_size:    1048576
lmm_layout_gen:     0
lmm_stripe_offset:  1
        obdidx           objid           objid           group
             1         4157803       0x3f716b               0
```

lfs getstripe.

```
[cozzini@elcid cozzini]$ lfs help setstripe
setstripe: Create a new file with a specific striping pattern or
set the default striping pattern on an existing directory or
delete the default striping pattern from an existing directory
usage: setstripe -d <directory>   (to delete default striping)
 or
usage: setstripe [--stripe-count|-c <stripe_count>]
                 [--stripe-index|-i <start_ost_idx>]
                 [--stripe-size|-S <stripe_size>]
                 [--pool|-p <pool_name>]
                 [--block|-b] <directory|filename>
       stripe_size:  Number of bytes on each OST (0 filesystem default)
                     Can be specified with k, m or g (in KB, MB and GB
                     respectively)
       start_ost_idx: OST index of first stripe (-1 default)
       stripe_count: Number of OSTs to stripe over (0 default, -1 all)
       pool_name:    Name of OST pool to use (default none)
       block:   Block file access during data migration
```

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Lustre – some advices to check

- Use ls -l only where absolutely necessary
- Avoid using wild cards with GNU commands,
- Place small files on single OST
- Place directories containing many small files on single OSTs
- Set the stripe count and size appropriately for shared files
- Set the stripe count appropriately for applications which utilize a file-per-process

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What you can do with setstripe ?

- 1.setting striping on a single file:
- 2.setting stripe on a directory:
  - Files within directory hinerits the same striping policy
- Note: you cannot change the striping policy of a file..
- To do this:
  - create a new file with appropriate striping policy and then move the original file over this.

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tips to use lustre at best

identify bottlenecks

- HDs, RAID, controllers, volumes and virtual disks, 10GE, iscsi, LUSTRE fs, local caching/buffers, InfiniBand or Gigabit network, LUSTRE client, access patterns

when accessing files:

- read/write in large chunks, not line by line

when running multiple I/O operations:

- optimize data distribution and disk access (i.e. mpi-i/o)

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