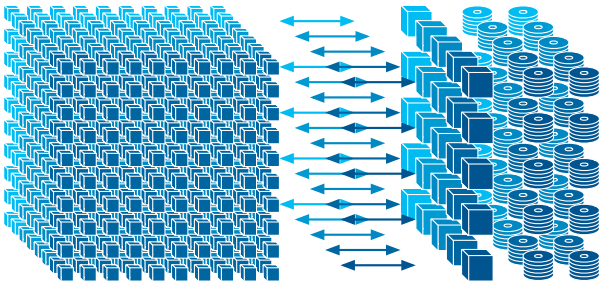
Introduction to Lustre* Architecture

Lustre* systems and network administration

October 2017

* Other names and brands may be claimed as the property of others

Lustre – Fast, Scalable Storage for HPC



Lustre* is an open-source, object-based, distributed, parallel, clustered file system

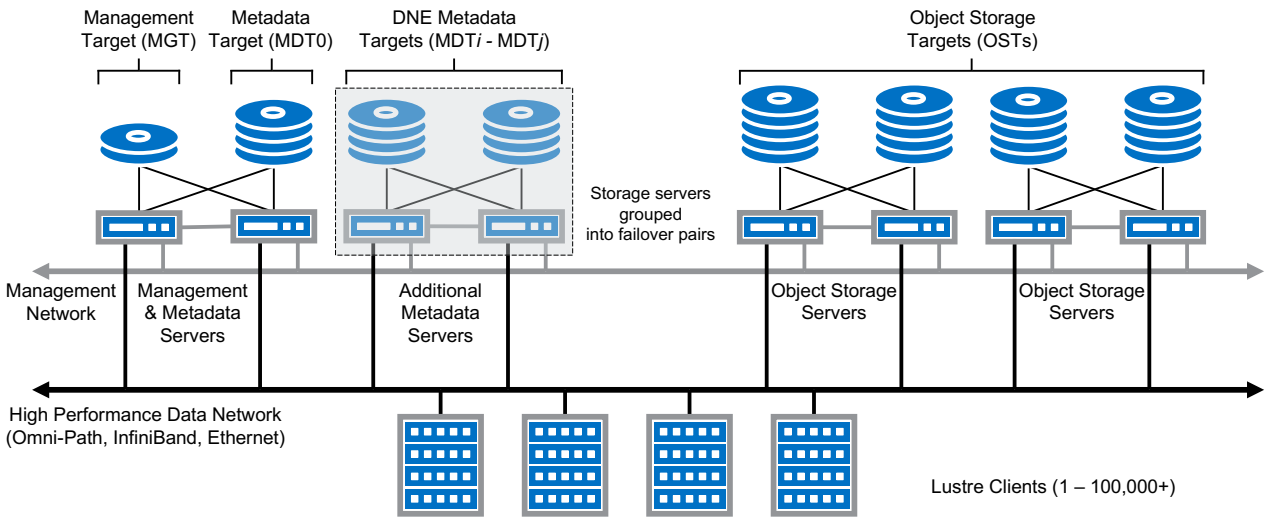
- Designed for maximum performance at massive scale
- Capable of Exascale capacities
- Highest IO performance available for the world's largest supercomputers
- POSIX compliant
- Efficient and cost effective

Lustre* is an open-source, distributed, parallel data storage platform designed for massive scalability, high-performance, and high-availability. Popular with the HPC community, Lustre is used to support the most demanding data-intensive applications. Lustre provides horizontally scalable IO for data centres of all sizes, and is deployed alongside some of the very largest supercomputers. The majority of the top 100 fastest computers, as measured by top500.org, use Lustre for their high performance, scalable storage.

Lustre file systems can scale from very small platforms of a few hundred terabytes up to large scale platforms with hundreds of petabytes, in a single, POSIX-compliant, name space. Capacity and throughput performance scale easily.

Lustre runs on Linux-based operating systems and employs a client-server network architecture. Lustre software services are implemented entirely within the Linux kernel, as loadable modules. Storage is provided by a set of servers that can scale to populations measuring up to several hundred hosts. Lustre servers for a single file system instance can, in aggregate, present up to tens of petabytes of storage to thousands of compute clients simultaneously, and deliver more than a terabyte-per-second of combined throughput.

Lustre Scalable Storage



Lustre's architecture uses distributed, object-based storage managed by servers and accessed by client computers using an efficient network protocol. There are metadata servers, responsible for storage allocation, and managing the file system name space, and object storage servers, responsible for the data content itself. A file in Lustre is comprised of a metadata inode object and one or more data objects.

Lustre is a client-server, parallel, distributed, network file system. Servers manage the presentation of storage to a network of clients, and write data sent from clients to persistent storage targets.

There are three different classes of server:

- Management server provides configuration information, file system registries
- Metadata servers record file system namespace, inodes. The metadata servers maintain the file system index.
- Object storage servers record file content in distributed binary objects. A single file is comprised of 1 or more objects, and the data for that file is organized in stripes across the objects. Objects are distributed across the available storage targets.

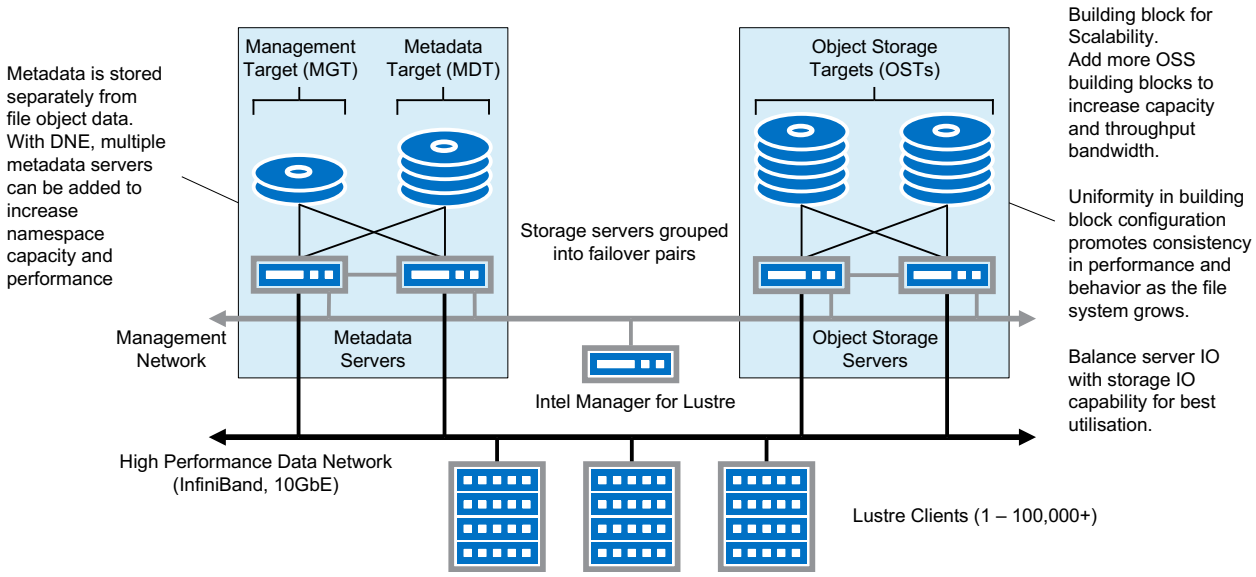
Lustre separates metadata (inode) storage from block data storage (file content). All file metadata operations (creating and deleting files, allocating data objects, managing permissions) are managed by the metadata servers. Metadata servers provide the index to the file system. Metadata is stored in key-value index objects that store file system inodes: file and directory names, permissions, block data locations, extended attributes, etc.

Lustre object storage servers write the data content out to persistent storage. Object servers can be written to concurrently, and individual files can be distributed across multiple objects on multiple servers. This allows very large files to be created and accessed in parallel by processes distributed across a network of computer infrastructure. Block data is stored in binary byte array data objects on a set of storage targets. A single Lustre "file" can be written to multiple objects across many storage targets.

In addition to the metadata and object data, there is the management service, which is used to keep track of servers, clients, storage targets and file system configuration parameters.

Clients aggregate the metadata name space and object data to present a coherent POSIX file system to applications. Clients do not access storage directly: all I/O is sent over a network. The Lustre client software splits IO operations into metadata and block data, communicating with the appropriate services to service IO transactions. This is the key concept of Lustre's design – separate small, random, IOPS-intensive metadata traffic from the large, throughput-intensive, streaming block IO.

Lustre Building Blocks



The major components of a Lustre file system cluster are:

- **MGS + MGT:** Management service, provides a registry of all active Lustre servers and clients, and stores Lustre configuration information. MGT is the management service storage target used to store configuration data.
- **MDS + MDTs:** Metadata service, provides file system namespace (the file system index), storing the inodes for a file system. MDT is the metadata storage target, the storage device used to hold metadata information persistently. Multiple MDS and MDTs can be added to provide metadata scaling.
- **OSS + OSTs:** Object Storage service, provides bulk storage of data. Files can be written in stripes across multiple object storage targets (OSTs). Striping delivers scalable performance and capacity for files. OSS are the primary scalable service unit that determines overall aggregate throughput and capacity of the file system.
- **Clients:** Lustre clients mount each Lustre file system instance using the Lustre Network protocol (LNet). Presents a POSIX-compliant file system to the OS. Applications use standard POSIX system calls for Lustre IO, and do not need to be written specifically for Lustre.
- **Network:** Lustre is a network-based file system, all IO transactions are sent using network RPCs. Clients have no local persistent storage and are often diskless. Supports many different network technologies, including OPA, IB, Ethernet.

Lustre Networking

Applications do not run directly on storage servers: all application I/O is transacted over a

network. Lustre network I/O is transmitted using a protocol called LNet, derived from the Portals network programming interface. LNet has native support for TCP/IP networks as well as RDMA networks such as Intel Omni-Path Architecture (OPA) and InfiniBand. LNet supports heterogeneous network environments. LNet can aggregate IO across independent interfaces, enabling network multipathing. Servers and clients can be multi-homed, and traffic can be routed using dedicated machines called LNet routers. Lustre network (LNet) routers provide a gateway between different LNet networks. Multiple routers can be grouped into pools to provide performance scalability and to provide multiple routes for availability.

The Lustre network protocol is connection-based: end-points maintain shared, coordinated state. Servers maintain exports for each active connection from a client to a server storage target, and clients maintain imports as an inverse of server exports. Connections are per-target and per-client: if a server exports *N* targets to *P* clients, there will be (*N* * *P*) exports on the server, and each client will have *N* imports from that server. Clients will have imports for every Lustre storage target from every server that represents the file system.

Most Lustre protocol actions are initiated by clients. The most common activity in the Lustre protocol is for a client to initiate an RPC to a specific target. A server may also initiate an RPC to the target on another server, e.g. an MDS RPC to the MGS for configuration data; or an RPC from MDS to an OST to update the MDS's state with available space data. Object storage servers never communicate with other object storage servers: all coordination is managed via the MDS or MGS. OSS do not initiate connections to clients or to an MDS. An OSS is relatively passive: it waits for incoming requests from either an MDS or Lustre clients.

Lustre and Linux

The core of Lustre runs in the Linux kernel on both servers and clients. Lustre servers have a choice of backend storage target formats, either LDISKFS (derived from EXT4), or ZFS (ported from OpenSolaris to Linux). Lustre servers using LDISKFS storage require patches to the Linux kernel. These patches are to improve performance, or to enable instrumentation useful during the automated test processes in Lustre's software development lifecycle. The list of patches continues to reduce as kernel development advances, and there are initiatives underway to completely remove customized patching of the Linux kernel for Lustre servers.

Lustre servers using ZFS OSD storage and Lustre clients do not require patched kernels. The Lustre client software is being merged into mainstream Linux kernel, and is available in kernel-staging.

Lustre and High Availability

Service availability / continuity is sustained using a High Availability failover resource management model, where multiple servers are connected to shared storage subsystems and services are distributed across the server nodes. Individual storage targets are managed as active-passive failover resources, and multiple resources can run in the same HA configuration for optimal utilisation. If a server develops a fault, then any Lustre storage

target managed by the failed server can be transferred to a surviving server that is connected to the same storage array. Failover is completely application-transparent: system calls are guaranteed to complete across failover events.

In order to ensure that failover is handled seamlessly, data modifications in Lustre are asynchronous and transactional. The client software maintains a transaction log. If there is a server failure, the client will automatically re-connect to the failover server and replay transactions that were not committed prior to the failure. Transaction log entries removed once the client receives confirmation that the IO has been committed to disk.

All Lustre server types (MGS, MDS and OSS) support failover. A single Lustre file system installation will usually be comprised of several HA clusters, each providing a discrete set of metadata or object services that is a subset of the whole file system. These discrete HA clusters are the building blocks for a high-availability, Lustre parallel distributed file system that can scale to tens of petabytes in capacity and to more than one terabyte-per-second in aggregate throughput performance.

Building block patterns can vary, which is a reflection the flexibility that Lustre affords integrators and administrators when designing their high performance storage infrastructure. The most common blueprint employs two servers joined to shared storage in an HA clustered pair topology. While HA clusters can vary in the number of servers, a two-node configuration provides the greatest overall flexibility as it represents the smallest storage building block that also provides high availability. Each building block has a well-defined capacity and measured throughput, so Lustre file systems can be designed in terms of the number of building blocks that are required to meet capacity and performance objectives.

An alternative to the two-node HA building block, described in Scalable high availability for Lustre with Pacemaker (video), was presented at LUG 2017 by Christopher Morrone. This is a very interesting design and merits consideration.

A single Lustre file system can scale linearly based on the number of building blocks. The minimum HA configuration for Lustre is a metadata and management building block that provides the MDS and MGS services, plus a single object storage building block for the OSS services. Using these basic units, one can create file systems with hundreds of OSSs as well as several MDSs, using HA building blocks to provide a reliable, high-performance platform.

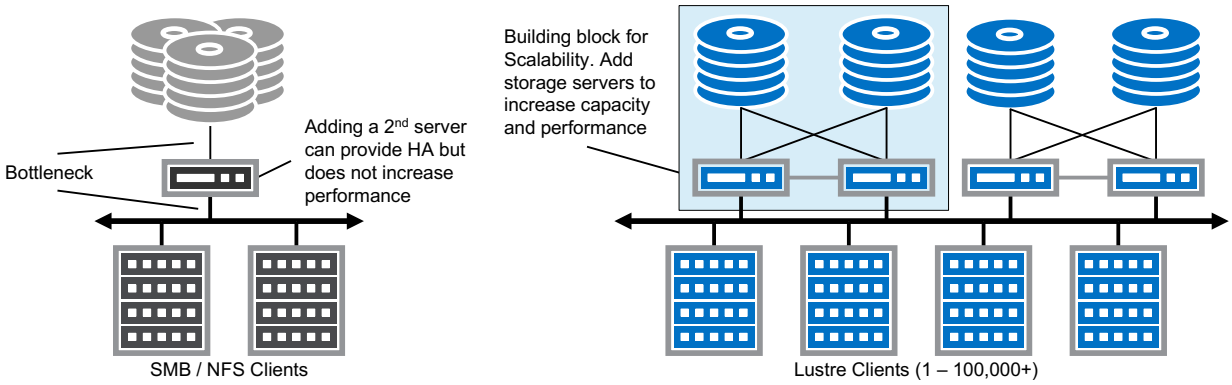
Lustre Storage Scalability

	Value using LDISKFS backend	Value using ZFS backend	Notes
Maximum stripe count	2000	2000	Limit is 160 for ldiskfs if "ea_inode" feature is not enabled on MDT
Maximum stripe size	< 4GB	< 4GB	
Minimum stripe size	64KB	64KB	
Maximum object size	16TB	256TB	
Maximum file size	31.25PB	512PB*	
Maximum file system size	512PB	8EB*	
Maximum number of files or subdirectories per directory	10M for 48-byte filenames. 5M for 128-byte filenames.	2^{48}	
Maximum number of files in the file system	4 billion per MDT	256 trillion per MDT	
Maximum filename length	255 bytes	255 bytes	
Maximum pathname length	4096 bytes	4096 bytes	Limited by Linux VFS

The values here are intended to reflect the potential scale of Lustre installations. The largest Lustre installations used in production today are measured in 10's of petabytes, with projections for 100's of petabytes within 2 years. Typical Lustre system deployments range in capacity from 1 – 60PB, in configurations that can vary widely, depending on workload requirements.

The values depicted for ZFS file system and file system size are theoretical, and in fact represent a conservative projection of the scalability of ZFS with Lustre. If one were to make a projection of ZFS scalability using the ZFS file system's own theoretical values, the numbers are so large as to be effectively meaningless in any useful assessment of capability.

Traditional Network File Systems vs Lustre



Distributed client, central server, e.g. NFS, SMB

Performance and scalability is limited by single server bandwidth

All clients use a single network path to one server

Adding a new storage server creates a separate file system

Storage becomes fragmented into silos

Distributed client, distributed servers (Lustre)

Scalable Metadata and Object Storage services

Scale performance and capacity linearly as client population grows

Client network scalability is not limited by the file system

All clients can access all storage servers simultaneously and in parallel

Single coherent name space across all servers. Can have hundreds of network storage servers in a single file system

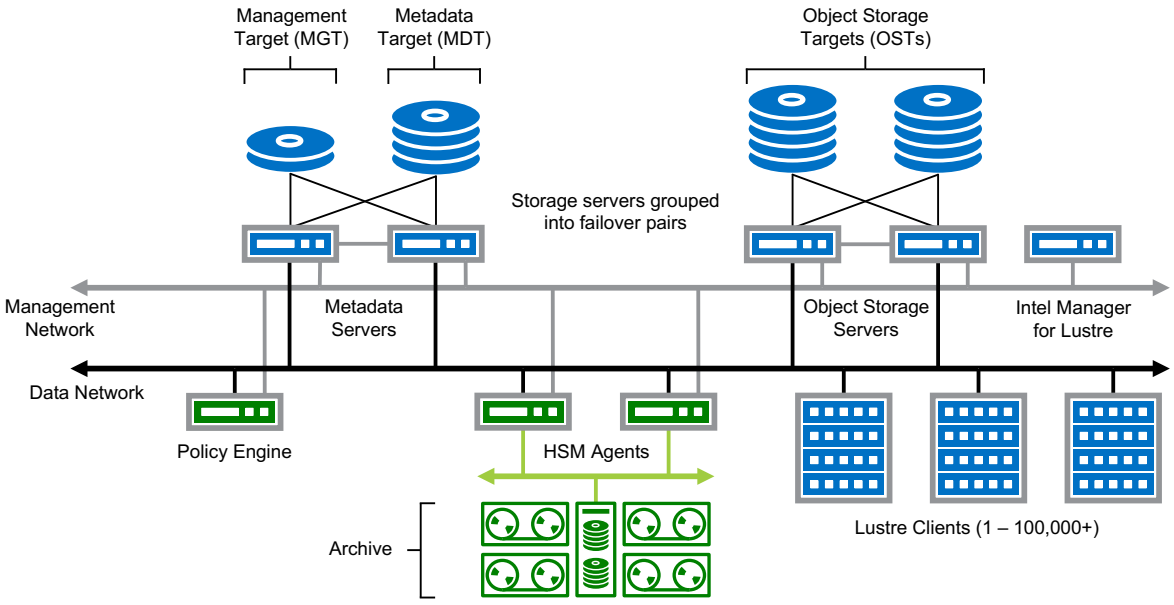
From its inception, Lustre has been designed to enable data storage to move beyond the bottlenecks imposed by limitations in hardware.

Lustre is a distributed network file system and shares some of the characteristics common to other network storage technology, namely that clients transact IO over a network and do not write data locally, the servers support concurrency, and the data is presented as a single coherent namespace.

Where Lustre differentiates itself from other network file systems, such as NFS or SMB, is in its ability to seamlessly scale both capacity and performance linearly to meet the demands of data-intensive applications with minimal additional administrative overhead. To increase capacity and throughput, add more servers with the required storage. Lustre will automatically incorporate new servers and storage, and the clients will leverage the new capacity automatically. New capacity is automatically incorporated into the pool of available storage.

Contrast this to traditional NFS deployments where capacity is often carved up into vertical silos based on project or department, and presented to computers using complex automount maps that need to be maintained. Available capacity is often isolated and it is difficult to balance utilisation, while performance is constrained to the capability of a single machine.

Lustre HSM System Architecture



Hierarchical Storage Management (HSM) is a collection of technologies and processes designed to provide a cost-effective storage platform that balances performance, capacity and long term retention (archival). Storage systems are organized into tiers, where the highest-performance tier is on the shortest path to the systems where applications are running; this is where the most active, or hottest, data is generated and consumed. As the high-performance tier fills, data that is no longer being actively used (cooler data) will be migrated to higher-capacity and generally lower-cost-per-terabyte storage platforms for long-term retention. Data migration should ideally be managed automatically and transparently to the end user.

Lustre provides a framework for incorporating an HSM tiered storage implementation. Lustre fulfills the high performance storage tier requirement. When a file is created, a replica can be made on the associated HSM archive tier, so that two copies of the file exist. As changes are made to the file, these are replicated onto the archive copy as well. The process of replicating data between Lustre and the archive is asynchronous, so there will be a delay in data generated on Lustre being reflected in the archive tier. As the available capacity is gradually consumed on the Lustre tier, the older, least frequently used files are "released" from Lustre, meaning that the local copy is deleted from Lustre and replaced with a reference that points to the archive copy. Applications are not aware of the locality of a file: from the application's perspective, files are accessed using the same system calls. Crucially, applications do not need to be re-written in order to work with data stored on an HSM system. If a system call is made to open a file that has been released (i.e. a file whose contents are located on the archive tier only), the HSM software automatically dispatches a request to retrieve the file from the archive and restore it to the Lustre file system. This may be noticeable in the form

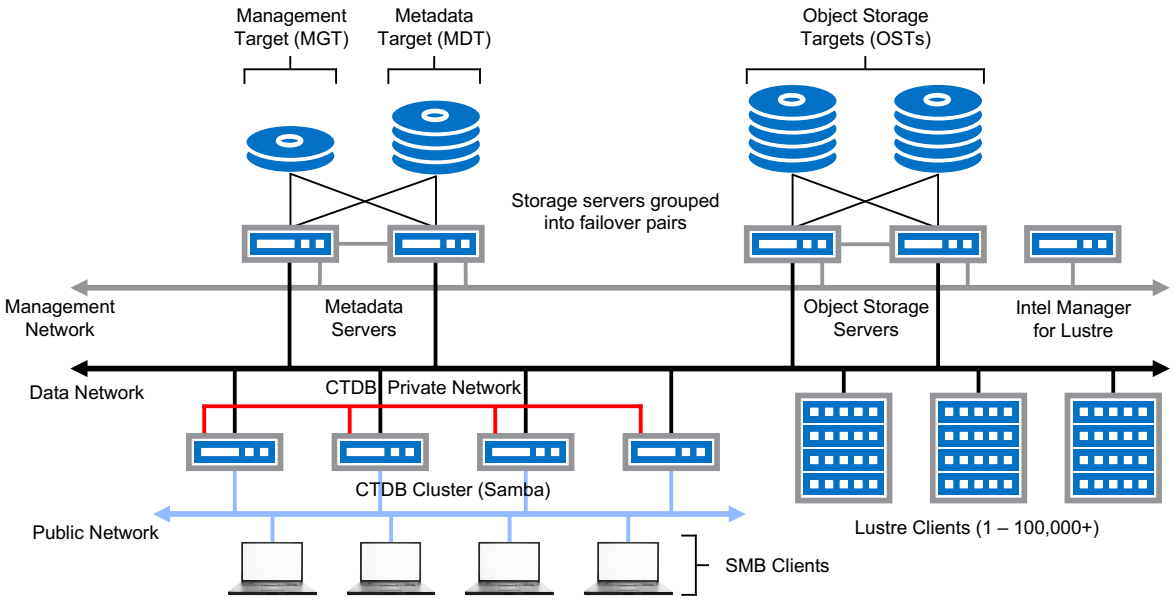
of a delay, but is otherwise transparent to the application.

The diagram provides an overview of the hardware architecture for a typical Lustre + HSM file system. The metadata servers have an additional process called the HSM Coordinator that accepts, queues and dispatches HSM requests (this may also be referred to this as the MDT Coordinator since the process runs on the metadata server – MDS). HSM commands are submitted from Lustre clients, either through the command line or through a special-purpose third-party application known as a Policy Engine. The Policy Engine software makes use of Lustre's HSM API to interact with the HSM Coordinator. The HSM platform also requires an interface between the Lustre file system tier and the archive tier. Servers called HSM Agents (also known as Copytool servers) provide this interface.

Lustre provides reference implementations of the HSM Copytool. The copytool supplied with Lustre uses POSIX interfaces to copy data to and from the archive. While this implementation of copytool is completely functional, it has been created principally as an example of how to develop copytools for other archive types, which may use different APIs. The copytool included with the Lustre software is intended as a reference implementation, and while it is stable, it is not a high- performance tool and for that reason, may not be suitable for a production environment. There are also several 3rd party copytools available, supporting a range of archive storage systems.

The Policy Engine most commonly associated with Lustre is called Robinhood. Robinhood is an open-source application with support for HSM. Robinhood tracks changes to the file system, and records this information persistently in a relational database. Robinhood also analyses the database and takes action based on a set of rules (called policies) defined by the file system's maintainers. These rules govern how files and directories will be managed by the HSM system, and the conditions under which to take an action. Among other things, policies in Robinhood determine how often to copy files to the archive tier, and the criteria for purging files from the Lustre tier in order to release capacity for new data.

Lustre SMB Gateway System Architecture



Lustre was originally designed for HPC applications running on large clusters of Linux-based servers and can present extremely high-capacity file systems with high performance. As it has matured, Lustre has found roles in IT system infrastructure, and has become increasingly relevant to commercial enterprises as they diversify their workloads and invest in massively-parallel software applications.

This broadening of scope for high-performance computing, coupled with increasing data management expectations, is placing new demands on the technologies that underpin high-performance storage systems, including Lustre file systems. As a result, storage administrators are being asked to provide access to data held on Lustre file systems from a wide range of client devices and operating systems that are not normally supported by Lustre.

To address this need, a bridge is required between the Linux-based Lustre platform and other operating systems. The Samba project was originally created to fulfill this function for standalone UNIX file servers. Samba is a project that implements the Server Message Block (SMB) protocol originally developed by IBM and popularized by Microsoft Windows operating systems. SMB is common throughout computer networks. Samba provides computers with network-based access to files held on UNIX and Linux servers.

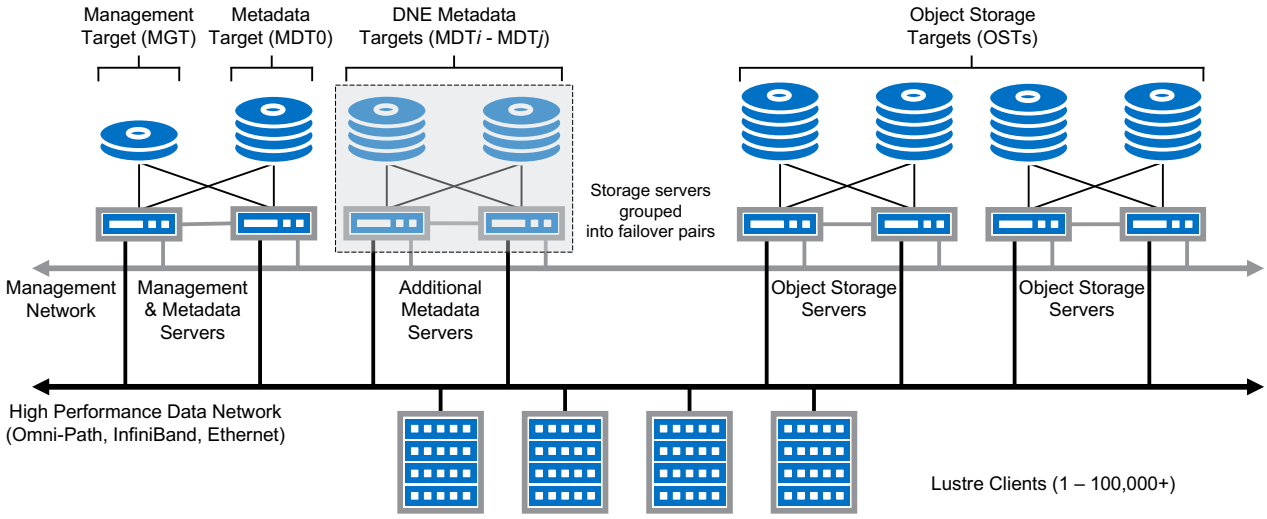
The Samba project developers also created a clustered software framework named Clustered Trivial Database (CTDB). CTDB is a network-based cluster framework and clustered database platform combined. CTDB is derived from the TDB database, which was originally developed for use by the Samba project. CTDB allows multiple Samba servers to safely and seamlessly

run in a cooperative cluster to serve data held on parallel file systems such as Lustre. CTDB provides a cluster framework and cluster-aware database platform that allows several Samba instances running on different hosts to run in parallel as part of a scalable, distributed service on top of a parallel file system. Each instance of Samba serves the same data on the same file system, using the CTDB framework to manage coherency and locking.

Samba, running on a CTDB cluster that is backed by Lustre, provides computer systems that don't have native support for Lustre with network access to the data held on a Lustre file system. By running Samba in a CTDB cluster backed by Lustre, one can create a parallel SMB service running across multiple hosts that can scale to meet demand.

Server Overview

Lustre File System Architecture – Server Overview



Each Lustre file system comprises, at a minimum:

- 1 Management service (MGS), with corresponding Management Target (MGT) storage
- 1 or more Metadata service (MDS) with Metadata Target (MDT) storage
- 1 or more Object storage service (OSS), with Object Storage Target (OST) storage

For High Availability, the minimum working configuration is:

- 2 Metadata servers, running MGS and MDS in failover configuration
    - MGS service on one node, MDS service on the other node
    - Shared storage for the MGT and MDT volumes
- 2 Object storage servers, running multiple OSTs in failover configuration
    - Shared storage for the OST volumes
    - All OSTs evenly balanced across the OSS servers

Management Service and Target

The MGS is a global resource that can be associated with one or more Lustre file systems. It acts as a global registry for configuration information and service state. It does not participate in file system operations, other than to coordinate the distribution of configuration information.

- Provides configuration information for Lustre file systems
- All Lustre components register with MGS on startup
- Clients retrieve information on mount

- Configuration information is stored on a storage target called the MGT
- There is usually only one MGT for a given network, and a Lustre file system will register with exactly one MGS

Metadata Service and Targets

The MDS serves the metadata for a file system. Metadata is stored on a storage target called the MDT. The MDS is responsible for the file system name space (the files and directories), and file layout allocation. It is the MDS that determines where files will be stored in the pool of object storage. Each Lustre file system must have at least one MDT served by an MDS, but there can be many MDTs on a server. The MDS is a scalable resource: using a feature called Distributed Namespace, a single file system can have metadata stored across many MDTs. The MGS and MDS are usually paired into a high availability server configuration.

- Records and presents the file system name space
- Responsible for defining the file layout (location of data objects)
- Scalable resource (DNE)

Object Storage Service (OSS) and Targets

- File content, stored as objects
- Files may be striped across multiple targets
- Massively Scalable

Object Storage Devices (OSDs)

Lustre targets run on a local file system on Lustre servers, the generic term for which is an "object storage device", or OSD. Lustre supports two kinds of OSD file systems for back-end storage:

- LDISKFS, a modified version of EXT4. This is the original persistent storage device layer for Lustre. Several features originally developed for Lustre LDISKFS have been incorporated into the EXT file system.
- ZFS, based on OpenZFS implementation from the ZFS on Linux project. ZFS is combines a volume manager and a file system into a single, coherent storage platform. ZFS is an extremely scalable file system and is well-suited for high-density storage systems. ZFS provides integrated volume management capabilities, RAID protection, data integrity protection, snapshots

Lustre* targets can be different types across servers in a single file system. Hybrid LDISKFS/ZFS file systems are possible, for example combining LDISKFS MDTs and ZFS OSTs, but generally it is recommended that for simplicity of administration, a file system uses a single OSD type. Lustre Clients are unaffected by the choice of OSD file system.

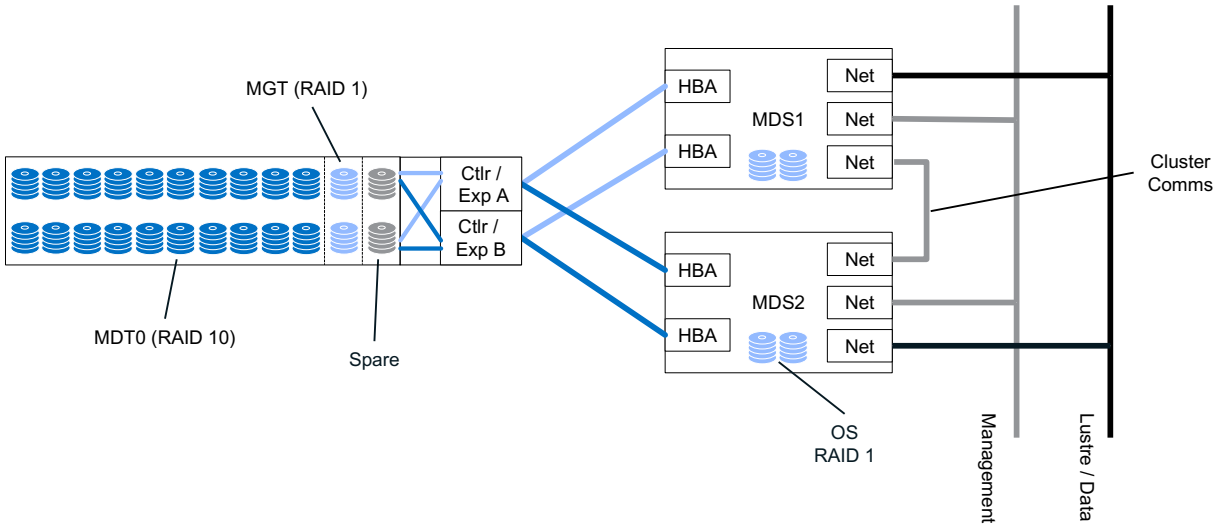
For the most part, a Lustre storage target is just a regular file system. The on-disk format comprises a few special directories for configuration files, etc. The Lustre ZFS OSD actually

bypasses the ZPL (ZFS POSIX Layer) to improve performance, but the on-disk format still maintains compatibility with the ZPL.

A storage target can be created on almost any Linux block device. Using a whole block device or ZFS pool is strongly preferred, but OSDs can be created on disk-partitions. LDISKFS OSDs will run on LVM. While not commonly used for the OSTs, LVM is useful for taking snapshots and making backups of the MDT: the MDT is the file system index, without which none of the data in Lustre is accessible, so it makes sense to regularly make a copy in case of a catastrophic hardware failure. While in principal, a device backup of the OSTs might be useful, the sheer scale of the task makes it impractical. Moreover, backups from the user-space Lustre clients is typically more effective and can target operationally critical data.

An alternative way to look at the problem is as follows: catastrophic loss of a single OST means that *some* of the data in the file system may be lost; whereas catastrophic loss of the root MDT means that *all* of the data is lost.

MGS and MGS Reference Design



Metadata Server Reference Design

The diagram above represents a typical design for a high-availability metadata server cluster. It comprises two server machines, each with three network interfaces, and a storage array that is connected to each machine.

The high performance data network is used for Lustre and other application traffic. Common transports for the data network are Intel Omni-path, InfiniBand or 10/40/100Gb Ethernet. The management network is used for systems management, monitoring and alerts traffic and to provide access to baseband management controllers (BMCs) for servers and storage. The dedicated secondary cluster network is a point-to-point, or cross-over cable, used exclusively for cluster communications, usually used in conjunction with the management network to ensure redundancy in the cluster communications framework.

Storage can be either a JBOD or an array with an integrated RAID controller.

The MDS has a high performance shared storage target, called the MDT (Metadata Target). Metadata performance is dependent upon fast storage LUNs with high IOPs characteristics. Metadata IO comprises very large rates of small, random transactions, and storage should be designed accordingly. Flash-based storage is an ideal medium to complement the metadata workload. Striped mirrors or RAID 1+0 arrangements are typical, and will yield the best overall performance while ensuring protection against hardware failure. Storage is sized for metadata IO performance, and a projection of the expected maximum number of inodes.

The MGS has a shared storage target, called the MGT (Management Target). MGT storage requirements are very small, typically 100MB. When a JBOD configuration is used, e.g. for ZFS-based storage, the MGT should be comprised of a single mirror of two drives – avoid the temptation to create a single ZFS pool that contains both an MGT and MDT dataset – this severely compromises the flexibility of managing resources in an HA cluster and creates an unnecessary colocation dependency. Moreover, when a failure event occurs, both MGT and MDT resources will need to failover at the same time, which will disable the imperative recovery feature in Lustre and increase the time it takes services to resume operation. Some intelligent storage arrays provide more sophisticated ways to carve out storage, allowing more fine-grained control and enabling a larger proportion of the available storage to be allocated to the MDT. The core requirement is to create a storage target that comprises a mirror to provide redundancy.

The use of spares is entirely at the discretion of the system designer. Note that when designing for ZFS, the use of the hot-spare feature is not recommended for shared storage failover configurations. Instead, if spare a required, use them as warm-standby devices (i.e. present in the chassis but not incorporated into the ZFS configuration directly). Warm standby's will require operator intervention to activate as a replacement when a drive fails, but will avoid issues with the hot spare capability in ZFS when used in HA. For example, any pool that is sharing a global spare cannot be exported while the spare is being used; and there is no arbitration or coordination of spare allocation across nodes – if two nodes make a simultaneous attempt to allocate the spare, there is a race to acquire the device, which makes the process unpredictable.

One pair of MDS servers can host multiple MDTs but only one MGT.

MGS

- Manages filesystem configuration and tunable changes, for clients, servers and targets.
- Registration point: new server and client components register with MGS during startup.
- Servers and clients obtain Lustre configuration from MGS during mount and configuration updates from MGS after mount. Think of it as a Directory service and global registry.
- One per site / per file system
- Each Lustre file system needs to register with an MGS
- A MGS can serve one or more Lustre file systems
- MGT stores global configuration information, provided upon request
- The MGT should be not co-located on the same volume as the metadata target (MDT), as the imperative recovery capability (critical, high speed recovery mechanism) of Lustre will be disabled if MDT and MGT are co-located
- Only one MGS service can run on a host: cannot mount multiple MGT volumes on a single host
- Storage requirements are minimal (approximately 100-200 MB). A single mirrored disk configuration is sufficient.
- Can run stand-alone but it is usually grouped with the root MDS (MDT0) of a file system in an HA failover cluster.

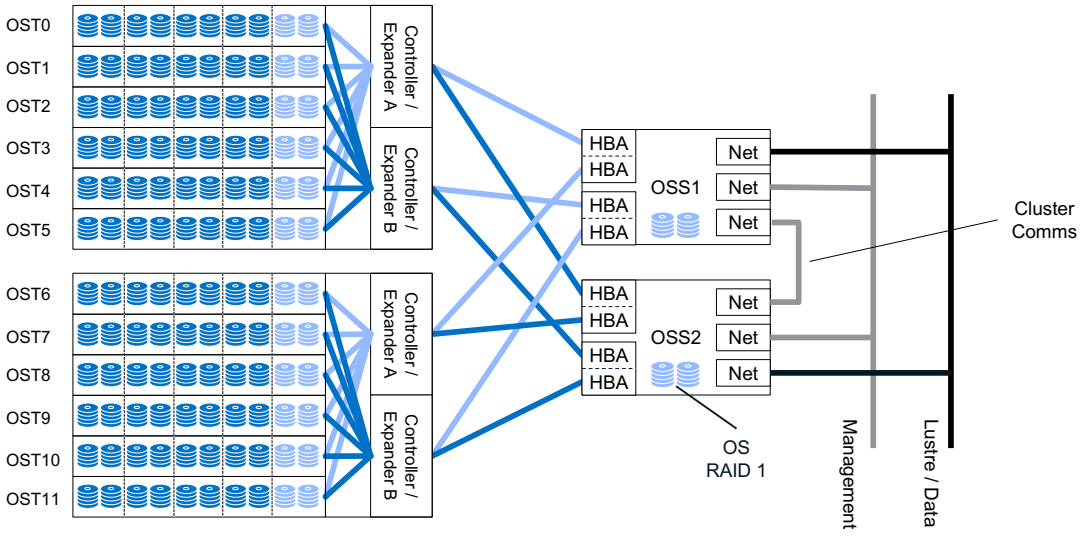
MDS

- One or more MDS per file system
- Significant multi-threaded CPU use
- Simultaneous access from many clients
- Maintains the metadata, which includes information seen via stat() – owner, group, filename, links, ctime, mtime, etc., and extended attributes, such as the File Identifier (FID)†, Mapping of FID, OSTs and Object ID's, Pool Membership, ACLs, etc.
- Metadata is stored on one or more MDTs
- An MDT stores metadata for exactly one Lustre file system
- Many MDTs can serve a single file system, by using the Distributed Namespace (DNE) feature
- Maximum of 4096 MDTs per Lustre file system
- File system is unavailable if MDT is unavailable
- MDT size is based on the amount of files expected in file system
    - Maximum of 4B inodes per MDT for ldiskfs MDT storage
    - For ZFS MDTs, inode capacity is limited only by the capacity of the storage volume

† FIDs are described in a later section.

OSS Reference Design

High density storage chassis based on 60 disks per tray, no spares



The diagram above represents a typical design for a high-availability object storage server cluster. It comprises two server machines, each with three network interfaces, and a storage array that is connected to each machine.

The high performance data network is used for Lustre and other application traffic. Common transports for the data network are Intel Omni-path, InfiniBand or 10/40/100Gb Ethernet. The management network is used for systems management, monitoring and alerts traffic and to provide access to baseband management controllers (BMCs) for servers and storage. The dedicated secondary cluster network is a point-to-point, or cross-over cable, used exclusively for cluster communications, usually used in conjunction with the management network to ensure redundancy in the cluster communications framework.

Storage can be either a JBOD or an array with an integrated RAID controller.

The Object storage servers provide the scalable bulk data storage for Lustre. IO transactions are typically large with correspondingly large RPC payloads and require high throughput bandwidth. Object storage servers move data between block storage devices and the network. The OSS is used to transfer data held on devices called Object Storage Targets (OSTs) to the Lustre clients, and manages read / write calls. Typically there are many Object Storage Servers for a single Lustre file system, and represent Lustre's core scalable unit: add more OSS servers to increase capacity and throughput performance. A minimum of 2 servers is required for high availability. The aggregate throughput of the file system is the sum of the throughput of each individual OSS and the total storage capacity of the Lustre file system is the sum of the capacities of all OSTs.

Each OSS may have several shared Object Storage Targets (OSTs), normally configured in a RAID 6 or equivalent parity-based redundant storage configuration. This provides the best balance of capacity, performance and resilience. The width, or number of disks, in each RAID group should be determined based on the specific capacity or performance requirements for a given installation. The historical precedent for RAID is to always create RAID groups that have N+P disks per group, where N is a power of 2 and P is the amount of parity. For example, for RAID 6, one might have ten disks: N=8 and P=2 (8+2). In many modern arrays, this rule may in fact be redundant, and in the case of ZFS, the rule has been demonstrated to be largely irrelevant. This is especially true when compression is enabled on ZFS, since the core premise of using a power of 2 for the layout was to ensure aligned writes for small block sizes that are also a power of 2, and also to support the idea of a full stripe write on RAID6 of 1MB without any read-modify-write overheads. These considerations do not generally apply to ZFS. Furthermore, when designing solutions for ZFS, most workloads benefit from enabling compression. When compression is enabled, the block sizes will not be a power of two, regardless of the layout, and workloads will benefit more from enabling compression in ZFS than from RAIDZ sizing. For more detailed information:

https://www.delphix.com/blog/delphix-engineering/zfs-raidz-stripe-width-or-how-i-learned-stop-worrying-and-love-raidz

For hardware RAID solutions, RAID 6 (8+2) is still one the most common configurations, but again, it is advised not to follow this rule blindly. Experiment with different layouts and try to maximise the overall capacity utilisation of the storage system.

An OSS pair may have more than one storage array. Two or four arrays or enclosures per OSS pair is common. Some high-density configurations may have more. To ensure that performance is consistent across server nodes, OST LUNs should be evenly distributed across the OSS servers.

File data is stored on OSTs in byte-array data objects. A single file system will comprise many OST volumes, to a maximum of 8150. The on-disk OST structure contains a few special directories for configuration files, etc., and the file system data which accessed via object IDs. Each object stores either a complete file (when stripe_count == 1) or part of a file (when stripe_count > 1). The capacity limit of an individual LDISKFS OST is 128TB. There is no theoretical limitation with ZFS, but volumes up to 256TB have been tested.

Client Overview

Lustre File System – Clients

Lustre client combines the metadata and object storage into a single, coherent POSIX file system

- Presented to the client OS as a file system mount point
- Applications access data as for any POSIX file system
- Applications do not therefore need to be re-written to run with Lustre

All Lustre client I/O is sent via RPC over a network connection

- Clients do not make use of any node-local storage, can be diskless

The Lustre client is kernel-based software that presents an aggregate view of the Lustre services to the host operating system as a POSIX-compliant file system. To applications, a Lustre client mount looks just like any other file system, with files organised in a directory hierarchy. A Lustre client mount will be familiar to anyone with experience of UNIX or Linux-based operating systems, and supports the features expected of a modern POSIX file system.

Lustre Client Services

Lustre employs a client-server model for communication. Each connection has an sender (the client end of the connection) and a receiver (the server process). The main client processes are as follows:

- **Management Client (MGC):** The MGC process handles RPCs with the MGS. All servers (even the MGS) run one MGC and every Lustre client runs one MGC for every MGS on the network.
- **Metadata Client (MDC):** The MDC handles RPCs with the MDS. Only Lustre clients initiate RPCs with the MDS. Each client runs an MDC process for each MDT.
- **Object Storage Client (OSC):** The OSC manages RPCs with a single OST. Both the MDS and Lustre clients initiate RPCs to OSTs, so each of these machines runs one OSC per OST

Lustre Network Routers

There is another Lustre service that is often seen in data centres, called a Lustre Network Router, or more commonly, an “LNet router”. The LNet router is used to direct Lustre IO

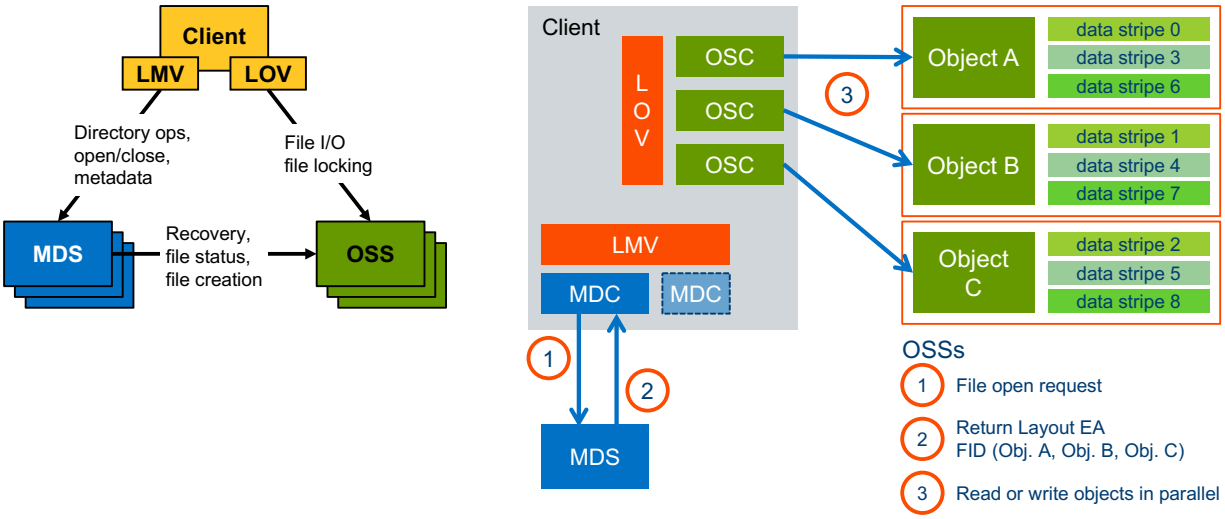
between different networks, and can be used to bridge different network technologies as well as routing between independent subnets. These routers are dedicated servers that do not participate as clients of a Lustre file system, but provide a way to efficiently connect different networks. For example, a router might be used to bridge a TCP/IP Ethernet fabric and an RDMA OmniPath (OPA) fabric, or provide a route between OPA and InfiniBand, or between two independent RDMA InfiniBand fabrics.

Routers are most commonly used to enable centralisation of Lustre server resources such that the file systems can be made available to multiple administrative domains within a data centre (e.g. to connect Lustre storage to multiple HPC clusters) or even between campuses over a wide-area network. Multiple routers can be deployed at the edge of a fabric to provide load-balancing and fault tolerance for a given route or set of routes.

Protocols Overview

Client IO, File IDs, Layouts

Overview of Lustre I/O Operations



The Lustre client software provides an interface between the Linux virtual file system and the Lustre servers. The client software is composed of several different services, each one corresponding to the type of Lustre service it interfaces to. A Lustre client instance will include a management client (MGC, not pictured), one or more metadata clients (MDC), and multiple object storage clients (OSCs), one corresponding to each OST in the file system.

The MGC manages configuration information. Each MDC transacts file system metadata requests to the corresponding MDT, including file and directory operations, and management of metadata (e.g. assignment of permissions), and each OSC transacts read and write operations to files hosted on its corresponding OST.

The logical metadata volume (LMV) aggregates the MDCs and presents a single logical metadata namespace to clients, providing transparent access across all the MDTs. This allows the client to see the directory tree stored on multiple MDTs as a single coherent namespace, and striped directories are merged on the clients to form a single visible directory to users and applications.

The logical object volume (LOV) aggregates the OSCs to provide transparent access across all the OSTs. Thus, a client with the Lustre file system mounted sees a single, coherent, synchronized namespace, and files are presented within that namespace as a single addressable data object, even when striped across multiple OSTs. Several clients can write to different parts of the same file simultaneously, while, at the same time, other clients can read from the file.

When a client looks up a file name, an RPC is sent to MDS to get a lock, which will be either one of the following:

- Read lock with look-up intent
- Write lock with create intent

The MDS returns a lock plus all the metadata attributes and file layout extended attribute (EA) to the client. The file layout information returned by the MDS contains the list of OST objects containing the file's data, and the layout access pattern describing how the data has been distributed across the set of objects. The layout information allows the client to access data directly from the OSTs. Each file in the file system has a unique layout: objects are not shared between files.

If the file is new, the MDS will also allocate OST objects for the file based on the requested layout when the file is opened for the first time. The MDS allocates OST objects by issuing RPCs to the object storage servers, which then create the objects and return object identifiers. By structuring the metadata operations in this way, Lustre avoids the need for further MDS communication once the file has been opened. After the file is opened, all transactions are directed to the OSSs, until the file is subsequently closed.

All files and objects in a Lustre file system are referenced by a unique, 128-bit, device-independent File Identifier, or FID. The FID is the reference used by a Lustre client to identify the objects for a file. Note that there is an FID for each data object on the OSTs as well as each metadata inode object on the MDTs. FIDs provide a replacement to UNIX inode numbers, which were used in Lustre releases prior to version 2.0.

When the mount command is issued on a Lustre client, the client will first connect to the MGS in order to retrieve the configuration information for the file system. This will include the location of the root of the file system, stored on MDT0. The client will then connect to the MDS that is running MDT0 and will mount the file system root directory.

Lustre inodes

Lustre inodes are MDT inodes

- Default inode size is 2K (actually an MDT inode is 512 bytes, plus up to 2K for EAs)
  - Metadata inode on-disk size is larger for ZFS
- The maximum number of inodes per MDT in LDISKFS is 4 billion, but there is no practical limit for ZFS

Lustre inodes hold all the metadata for Lustre files

Lustre inodes contain:

- Typical metadata from stat() (UID, GID, permissions, etc.)
- Extended Attributes (EA)

Extended Attributes contain:

- References to Lustre files (OSTs, Object ID, etc.)
- OST Pool membership, POSIX ACLs, etc.

Metadata storage allocation for inodes differs depending on the choice of back-end filesystem (LDISKFS or ZFS).

For LDISKFS metadata targets, the number of inodes for the MDT is calculated when the device is formatted. By default, Lustre will format the MDT using the ratio of 2KB-per-inode. The inode itself consumes 512 bytes, but additional blocks can be allocated to store extended attributes when the initial space is consumed. This happens for example, when a file has been striped across a lot of objects. Using this 2KB-per-inode ratio has proven to be a reliable way to allocate capacity for the MDT.

The LDISKFS filesystem imposes an upper limit of 4 billion inodes per MDT. By default, the MDT filesystem is formatted with one inode per 2KB of space, meaning 512 million inodes per TB of MDT space. In a Lustre LDISKFS file system, all the MDT inodes and OST objects are allocated when the file system is first formatted. When the file system is in use and a file is created, metadata associated with that file is stored in one of the pre-allocated inodes and does not consume any of the free space used to store file data. The total number of inodes on a formatted LDISKFS MDT or OST cannot be easily changed. Thus, the number of inodes created at format time should be generous enough to anticipate near term expected usage, with some room for growth without the effort of additional storage.

The ZFS filesystem dynamically allocates space for inodes and and inodes are allocated as needed, which means that ZFS does not have a fixed ratio of inodes per unit of MDT space. A minimum of 4kB of usable space is needed for each inode, exclusive of other overhead such as directories, internal log files, extended attributes, ACLs, etc.

With older ZFS on Linux releases (prior to 0.7.0), Lustre xattrs would exceed the allocated dnode space (512 bytes), and if 4KB sectors were used (ashift=12) then each MDT dnode would need (512+4096)*2 bytes of space (multiplied by 2 for the ditto copy, over and above mirrored VDEV). With dynamic dnodes in the newer releases (or with 512-byte sectors, which is increasingly rare) the space required is only (512+512)*2 bytes per dnode.

ZFS also reserves approximately 3% of the total storage space for internal and redundant metadata, which is not usable by Lustre. Since the size of extended attributes and ACLs is highly dependent on kernel versions and site-specific policies, it is best to over-estimate the amount of space needed for the desired number of inodes, and any excess space will be utilized to store more inodes. Note that the number of total and free inodes reported by `lfs df -i` for ZFS MDTs and OSTs is estimated based on the current average space used per inode. When a ZFS filesystem is first formatted, this free inode estimate will be very conservative (low) due to the high ratio of directories to regular files created for internal Lustre metadata storage, but this estimate will improve as more files are created by regular users and the average file size will better reflect actual site usage.

A Lustre file system uses extended attributes (EAs) contained in the metadata inode to store additional information about a file. Examples of extended attributes are ACLs, layout (e.g. striping) information, and the unique Lustre file identifier (FID) of the file. The layout EA contains a list of all object IDs and their locations (that is, the OSTs that contain the objects).

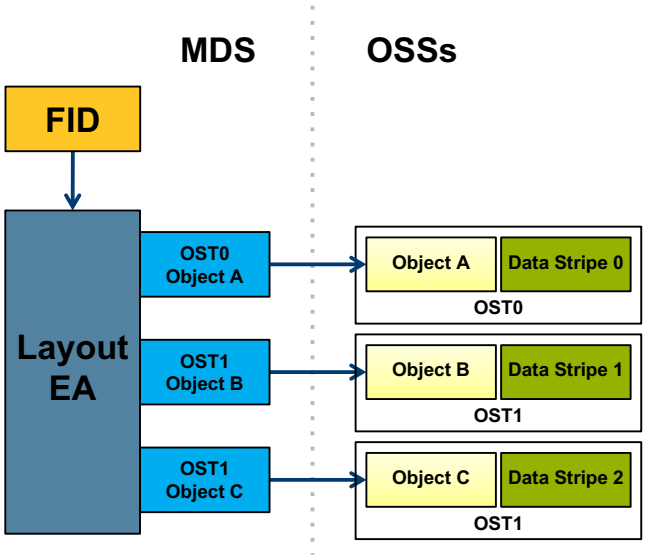
For files with very wide stripes, the layout EA may be too large to store in the inode and will be stored in separate blocks. Be careful when defining the layout for files, and try to make sure that the layout is only as large / wide as needed: storing the EA in the inode whenever possible avoids an extra, potentially expensive, disk seek.

Lustre internally uses a 128-bit file identifier (FID) for all files. To interface with user applications, the 64-bit inode numbers are returned by the `stat()`, `fstat()`, and `readdir()` system calls on 64-bit applications, and 32-bit inode numbers to 32-bit applications.

Layout EA

Layout EA is an extended attribute stored as part of a file's metadata on the MDT:

- A list of FIDs, used to locate the file data objects on the OST(s)
- The layout EA points to 1-to-N OST object(s) on the OST(s) that contain the file data
- If the layout EA points to one object, all the file data is stored entirely in that object.
- If the layout EA points to more than one object, the file data is striped across the objects using RAID 0, and each object is stored on a different OST



When a client wants to read from or write to a file, it first fetches the list of object FIDs containing the file's data from the MDT inode for the file. The client then uses this information to connect directly to the object storage servers where the data objects are stored and transact I/O on the file.

Information about where file data is located on the OST(s) is stored as an extended attribute called the ***layout EA***. The layout EA is stored in an MDT inode identified by the FID for the file. If the file is a regular file (not a directory or symbol link), the MDT inode points to 1-to-N OST object(s) on the OST(s) that contain the file data. If the MDT layout EA points to one object, all the file data is stored in that object. If the layout EA points to more than one object, the file data is *striped* across the objects using RAID 0, and each object is stored on a different OST.

File Layout: Striping

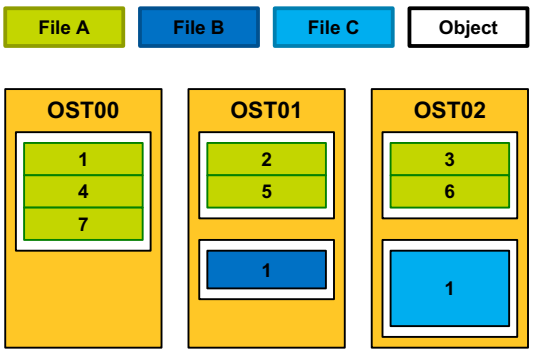
Each file in Lustre has its own unique file layout, comprised of 1 or more objects in a stripe equivalent to RAID 0

File layout is allocated by the MDS

Layout is selected by the client, either

- by policy (inherited from parent directory)
- by the user or application

Layout of a file is fixed once created



One of the main factors leading to the high performance of Lustre file systems is the ability to stripe data across multiple OSTs in a round-robin fashion. Users can optionally configure the number of stripes, stripe size, and OSTs that are used for each file. Striping can be used to improve performance enabling the aggregate bandwidth to a single file to exceed the bandwidth of a single OST. The ability to stripe is also useful when a single OST does not have enough free space to hold an entire file.

Striping allows segments or 'chunks' of data in a file to be stored on different OSTs. In the Lustre file system, a RAID 0 pattern is used in which data is "striped" across a certain number of objects. The number of objects in a single file is called the stripe_count. Each object contains chunks of data from the file, and chunks are written to the file in a circular round-robin manner. When the chunk of data being written to a particular object exceeds the stripe size, the next chunk of data in the file is stored on the next object.

When reading the data back from a file, the client needs to know the location of the OST objects, the starting object, and the stripe width (or chunk size) in order to correctly retrieve the file's data with the same pattern that was used to write the file.

The maximum number of objects that can be used to store a single file is 2000, i.e. this is the maximum number of OSTs that a single file can be striped across. File systems can be comprised of more than 2000 OSTs, but a single file within that file system is restricted to no more than 2000 OSTs, which puts an effective limit on the aggregate bandwidth for a single file. It is, of course, a rather large limit. The size of a single object is governed by the underlying storage file system, and the physical constraints of the hardware.

Lustre File Identifier (FID)

Lustre file identifiers (FIDs) provide a device-independent replacement for UNIX inode numbers to uniquely identify files or objects

A File Identifier (FID) is a unique 128-bit identifier for Lustre files and objects, comprising:

- 64-bit sequence number – used to locate the storage target
  - Unique across all OSTs and MDTs in a file system
- 32-bit object identifier (OID) – reference to the object within the sequence
- 32-bit version number – currently unused; reserved for future work

FID-in-dirent feature stores the FID as part of the name of the file in the parent directory

- Significantly improves performance for “ls” command executions by reducing disk I/O
- The FID-in-dirent is generated at the time the file is created
- Introduced in Lustre 2.0, FID-in-dirent is not compatible with the Lustre version 1.8 format

Introduced in Lustre software release 2.0, Lustre file identifiers (FIDs) replace UNIX inode numbers for identifying files or objects. FIDs are independent of the underlying file system OSD, and enabled support for multiple MDTs (introduced in Lustre software release 2.4) and ZFS (introduced in Lustre software release 2.4). Also introduced in release 2.0 is an LDISKFS feature named FID-in-dirent (also known as dirdata) in which the FID is stored as part of the name of the file in the parent directory. This feature significantly improves performance when executing commands like ls, by reducing disk I/O. The FID-in-dirent is generated at the time the file is created.

An FID is a 128-bit identifier that contains a unique 64-bit sequence number, a 32-bit object ID (OID), and a 32-bit version number. The sequence number is unique across all Lustre targets in a file system (OSTs and MDTs). FIDs are not bound to a specific target, they are never re-used and FIDs can be generated by Lustre clients.

Sequences are granted to clients by servers. A sequence number is unique across all Lustre targets (OSTs and MDTs) in a file system. When a client connects to a Lustre file system, a new FID sequence is allocated. The sequence is discarded when the client disconnects, and it is not re-used. When the client reconnects with the file system, a new sequence will be allocated. Each sequence has a limited number of FIDs (128,000) which may be created within its range. When the sequence is exhausted, a new sequence is started.

Sequence controller (MDT0) allocates super-sequence ranges to sequence managers. A super-sequence is a large contiguous range of sequence numbers. Sequence managers control distribution of sequences to clients, preventing FID collisions. The MDS and OSS

servers for a file system are all sequence managers. Ranges of sequence IDs are granted by managers to Lustre clients as reservations, which allows the client to create the FID for new files using a reserved sequence ID. When the existing allocation is exhausted, a new set of sequence numbers is provided. A given sequence ID always maps to the same storage target, and objects created within same sequence will be located on the same storage target.

An FID does not contain any location information. To determine the location of an object from its FID, Lustre has the FID location database (FLDB). The FLDB is a database mapping a sequence of FIDs to the specific target (MDT or OST) that manages the objects within the sequence. The complete FLDB for a file system is on on MDT0. When DNE is enabled, every MDT also has its own local FLD, a subset of the full FLDB. The FLDB is cached by all clients and servers in the file system, but is typically only modified when new servers are added to the file system.

The underlying filesystem still operates on inodes. An object index is stored on disk to handle FID to on-disk inode mapping.

Locking

Distributed lock manager in the manner of OpenVMS

Cache-coherent across all clients

Metadata server uses inode bit locks for file lookup, state (modification, open r/w/x), EAs and layout

- Clients can fetch multiple bit locks for an inode in a single RPC
- MDS manages all inode modifications to avoid lock resource contention

Object storage servers provide extent-based locks for OST objects

- File data locks are managed for each OST
- Clients can be granted read extent locks for part or all of the file, allowing multiple concurrent readers of the same file
- Clients can be granted non-overlapping write extent locks for regions of the file
- Multiple Lustre clients may access a single file concurrently for both read and write, avoiding bottlenecks during file I/O

Lustre implements byte-granular file and fine-grained metadata locking. Multiple clients can read and modify the same file or directory concurrently. The Lustre distributed lock manager (LDLM) ensures that files are coherent between all clients and servers in the file system. The MDT LDLM manages locks on inode permissions and pathnames. Each OST has its own LDLM for locks on file stripes stored thereon, which scales locking performance as the file system grows.

The LDLM also plays a part in resolving client failures. Recovery from client failure in a Lustre file system is based on lock revocation and other resources, so surviving clients can continue their work uninterrupted. If a client fails to respond to a blocking lock callback from the Distributed Lock Manager (DLM), or fails to communicate with the server for a long period of time (i.e., no pings), the client is forcibly removed from the cluster (evicted). This enables other clients to acquire locks blocked by the dead client's locks, and also frees resources (file handles, export data) associated with that client.

Glossary

Just so there's no confusion…

DNE - Distributed Namespace Environment - feature to aggregate multiple MDTs (possibly on many MDS's) into a single filesystem namespace

IDIF - OST object ID In FID - specific FID range reserved for compatibility with pre-DNE OST objects

IGIF - Inode and Generation In FID - specific FID range reserved for compatibility from Lustre 1.x MDT inode objects

FID - File IDentifier - unique 128-bit identifier for every object within a single filesystem.

LMV - Logical Metadata Volume - client software layer that handles client (llite) access to multiple MDTs

LOD - Logical Object Device - MDS software layer that handles access to multiple MDTs and multiple OSTs

LOV - Logical Object Volume - client software layer that handles client (llite) access to multiple OSTs

MDC - MetaData Client - client software layer that interfaces to the MDS

MDD - Metadata Device Driver - MDS software layer that understands POSIX semantics for file access

MDS - MetaData Server - software service that manages access to filesystem namespace (inodes, paths, permission) requests from the client.

MDT - MetaData Target - storage device that holds the filesystem metadata (attributes, inodes, directories, xattrs, etc)

MGS - Management Server - service that helps clients and servers with configuration

MGT - Management Target - storage device that holds the configuration logs

OFD - Object Filter Device - OSS software layer that handles file IO

OSC - Object Storage Client - client software layer that interfaces to the OST

OSD - Object Storage Device - server software layer that abstracts MDD and OFD access to underlying disk filesystems like ldiskfs and ZFS

OSP - Object Storage Proxy - server software layer that interfaces from one MDS to the OSD on another MDS or another OSS

OSS - Object Storage Server - software service that manages access to filesystem data (read, write, truncate, etc)

OST - Object Storage Target - storage device that holds the filesystem data (regular data files, not directories, xattrs, or other metadata)

Further Reading and References

Lustre Community

- http://lustre.org

Open Scalable File Systems (OpenSFS)

- http://opensfs.org/

European Open File Systems

- https://www.eofs.eu/

Download Lustre

- https://wiki.hpdd.intel.com/display/PUB/Lustre+Releases

Lustre Source Code

- git://git.hpdd.intel.com/fs/lustre-release.git

Lustre Management and Monitoring

- https://github.com/intel-hpdd/intel-manager-for-lustre

Lustre Systems Administration Guide

- http://wiki.lustre.org/Category:Lustre_Systems_Administration

Lustre Reference Manual

- http://lustre.org/documentation