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Second Edition

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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National Center for Computational Sciences

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ACRONYMS

HPC	High Performance Computing
ORNL	Oak Ridge National Laboratory
API	Application Programming Interface
GNU	GNU's Not Unix
DDN	DataDirect Networks
POSIX	Portable Operating System Interface
LFSCK	Lustre File System Checker
ZFS	Z File System
Ext4	Fourth Extended File System
RDMA	Remote Direct Memory Access
TCP	Transmission Control Protocol
MMP	Multiple Mount Protection
ACL	Access Control List
SSK	Shared-Secret Key
MGS	Management Server
MGT	Management Target
MDS	Metadata Server
MDT	Metadata Target
OSS	Object Storage Server
OST	Object Storage Target
FDR	Fourteen Data Rate
IB	Infiniband
OPA	Omni-Path Architecture
LNet	Lustre Networking
RAID	Redundant Array of Independent Disks
PFL	Progressive File Layout
DoM	Data on MDT
SEL	Self Extending Layout
DNE	Distributed Namespace
EA	Extended Attribute
OSC	Object Storage Client
LMV	Logical Metadata Volume
VFS	Virtual File System
LOV	Logical Object Volume
PTL-RPC	Portal Remote Procedure Call
LDLM	Lustre Distributed Lock Manager
OBD	Object Based Disk
OFD	OBD Filter Device
OSD	Object Storage Device
MDC	Metadata Client
LTS	Lustre Test Suites
HSM	Hierarchical Storage Manager
IOR	Interleaved or Random
MGC	Management Client

LRU	Least Recently Used
FLD	FID Location Database
FID	File Identifier
LWP	Light Weight Proxy
CPT	CPU Partition Table
NUMA	Non-Uniform Memory Access
SMP	Symmetric Multi-Processing
OSP	Object Storage Proxy
OI	Object Index
IGIF	Inode and Generation In FID
IDIF	Object ID In FID
UUID	Universally Unique Identifier
NID	Network Identifier

ABSTRACT

The Lustre file system has become a preferred storage resource for systems on the Top500 list, and it is often the file system of choice for small- to medium-sized HPC systems that require parallel shared access to data. Several resources exist to help users deploy and configure Lustre, but the same cannot be said for resources that explain the inner workings of the Lustre source code. A previous ORNL technical report entitled "Understanding Lustre Filesystem Internals" (ORNL/TM-2009/117) provided an excellent summary of Lustre subsystem operations. However, that report is over a decade old and is based on Lustre version 1.6. Since that report was published, Lustre has evolved significantly. Several subsystems underwent significant code changes and many new features have been added to the file system, bringing the current Lustre version up to 2.15.

This report aims to document and explain the internal workings of the latest version of the Lustre file system. It will provide more complete and up-to-date information than the previous technical report and should serve as a foundational document for anyone interested in Lustre software development. Key data structures will be described along with the APIs used for interaction among the various Lustre subsystems. Although the Lustre software is constantly being developed, the details in this document should remain relevant for the forseeable future.

1. Lustre Architecture

1.1 What is Lustre?

Lustre is a GNU General Public licensed, open-source distributed parallel file system developed and maintained by DataDirect Networks (DDN). Due to the extremely scalable architecture of the Lustre file system, Lustre deployments are popular in scientific supercomputing, as well as in the oil and gas, manufacturing, rich media, and finance sectors. Lustre presents a POSIX interface to its clients with parallel access capabilities to the shared file objects. As of this writing, Lustre is the most widely used file system on the top 500 fastest computers in the world. Lustre is the file system of choice on 7 out of the top 10 fastest computers in the world today, over 70% of the top 100, and also for over 60% of the top 500 [5].

1.2 Lustre Features

Lustre is designed for scalability and performance. The aggregate storage capacity and file system bandwidth can be scaled up by adding more servers to the file system, and performance for parallel applications can often be increased by utilizing more Lustre clients. Some practical limits are shown in Table 2 along with values from known production file systems.

Lustre has several features that enhance performance, usability, and stability. Some of these features include:

- POSIX Compliance: With few exceptions, Lustre passes the full POSIX test suite. Most operations are atomic to ensure that clients do not see stale data or metadata. Lustre also supports mmap() file IO.
- Online file system checking: Lustre provides a file system checker (LFSCK) to detect and correct file system inconsistencies. LFSCK can be run while the file system in online and in production, minimizing potential downtime.

- Controlled file layouts: The file layouts that determine how data is placed across the Lustre servers can be customized on a per-file basis. This allows users to optimize the layout to best fit their specific use case.
- Support for multiple backend file systems: When formatting a Lustre file system, the underlying storage can be formatted as either ldiskfs (a performance-enhanced version of ext4) or ZFS.
- Support for high-performance and heterogeneous networks: Lustre can utilize RDMA over low latency networks such as Infiniband or Intel OmniPath in addition to supporting TCP over commodity networks. The Lustre networking layer provides the ability to route traffic between multiple networks making it feasible to run a single site-wide Lustre file system.
- High-availability: Lustre supports active/active failover of storage resources and multiple mount protection (MMP) to guard against errors that may results from mounting the storage simultaneously on multiple servers. High availability software such as Pacemaker/Corosync can be used to provide automatic failover capabilities.
- Security features: Lustre follows the normal UNIX file system security model enhanced with POSIX ACLs. The root squash feature limits the ability of Lustre clients to perform privileged operations. Lustre also supports the configuration of Shared-Secret Key (SSK) security.
- Capacity growth: File system capacity can be increased by adding additional storage for data and metadata while the file system in online.

1.3 Lustre Components

Lustre is an object-based file system that consists of several components:

- Management Server (MGS) - Provides configuration information for the file system. When mounting the file system, the Lustre clients will contact the MGS to retrieve details on how the file system is configured (what servers are part of the file system, failover information, etc.). The MGS can also proactively notify clients about changes in the file system configuration and plays a role in the Lustre recovery process.
- Management Target (MGT) - Block device used by the MGS to persistently store Lustre file system configuration information. It typically only requires a relatively small amount of space (on the order to 100 MB).
- Metadata Server (MDS) - Manages the file system namespace and provides metadata services to clients such as filename lookup, directory information, file layouts, and access permissions. The file system will contain at least one MDS but may contain more.
- Metadata Target (MDT) - Block device used by an MDS to store metadata information. A Lustre file system will contain at least one MDT which holds the root of the file system, but it may contain multiple MDTs. Common configurations will use one MDT per MDS server, but it is possible for an MDS to host multiple MDTs. MDTs can be shared among multiple MDSs to support failover, but each MDT can only be mounted by one MDS at any given time.
- Object Storage Server (OSS) - Stores file data objects and makes the file contents available to Lustre clients. A file system will typically have many OSS nodes to provide a higher aggregate capacity and network bandwidth.

Table 2. Lustre scalability and performance numbers

Feature	Current Practical Range	Known Production Usage
Client Scalability	100 - 100,000	50,000+ clients, many in the 10,000 to 20,000 range
Client Performance	*Single client*: 90% of network bandwidth *Aggregate*: 10 TB/s	*Single client*: 4.5 GB/s (FDR IB, OPA1), 1000 metadata ops/sec *Aggregate*: 2.5 TB/s
OSS Scalability	*Single OSS*: 1-32 OSTs per OSS *Single OST (ldiskfs)*: 300M objects, 256TiB per OST *Single OST (ZFS)*: 500M objects, 256TiB per OST *OSS count*: 1000 OSSs w/ up to 4000 OSTs	*Single OSS (ldiskfs)*: 32x8TiB OSTs per OSS, 8x32TiB OSTs per OSS *Single OSS (ZFS)*: 1x72TiB OST per OSS *OSS count*: 450 OSSs w/ 1000 4TiB OSTs, 192 OSSs w/ 1344 8TiB OSTs, 768 OSSs w/ 768 72TiB OSTs
OSS Performance	*Single OSS*: 15 GB/s *Aggregate*: 10 TB/s	*Single OSS*: 10 GB/s *Aggregate*: 2.5 TB/s
MDS Scalability	*Single MDS*: 1-4 MDTs per MDS *Single MDT (ldiskfs)*: 4 billion files, 8 TiB per MDT *Single MDT (ZFS)*: 64 billion files, 64 TiB per MDT *MDS count*: 256 MDSs w/ up to 265 MDTs	*Single MDS*: 3 billion files *MDS count*: 7 MDSs w/ 7x 2 TiB MDTs in production (256 MDSs w/ 256 64 GiB MDTs in testing)
MDS Performance	50,000 create ops/sec, 200,000 metadata stat ops/sec	15,000 create ops/sec, 50,000 metadata stat ops/sec
File system Scalability	*Single File (max size)*: 32 PiB (ldiskfs) or 2^{63} bytes (ZFS) *Aggregate*: 512 PiB total capacity, 1 trillion files	*Single file (max size)*: multi-TiB *Aggregate*: 55 PiB capacity, 8 billion files

- Object Storage Target (OST) - Block device used by an OSS node to store the contents of user files. An OSS node will often host several OSTs. These OSTs may be shared among multiple hosts, but just like MDTs, each OST can only be mounted on a single OSS at any given time. The total capacity of the file system is the sum of all the individual OST capacities.

- Lustre Client - Mounts the Lustre file system and makes the contents of the namespace visible to the users. There may be hundreds or even thousands of clients accessing a single Lustre file sysyem. Each client can also mount more than one Lustre file system at a time.

- Lustre Networking (LNet) - Network protocol used for communication between Lustre clients and servers. Supports RDMA on low-latency networks and routing between heterogeneous networks.

The collection of MGS, MDS, and OSS nodes are sometimes referred to as the “frontend”. The individual OSTs and MDTs must be formatted with a local file system in order for Lustre to store data and metadata on those block devices. Currently, only ldiskfs (a modified version of ext4) and ZFS are supported for this purpose. The choice of ldiskfs or ZFS if often referred to as the “backend file system”. Lustre provides an abstraction layer for these backend file systems to allow for the possibility of including other types of backend file systems in the future.

Figure 1 shows a simplified version of the Lustre file system components in a basic cluster. In this figure, the MGS server is distinct from the MDS servers, but for small file systems, the MGS and MDS may be combined into a single server and the MGT may coexist on the same block device as the primary MDT.

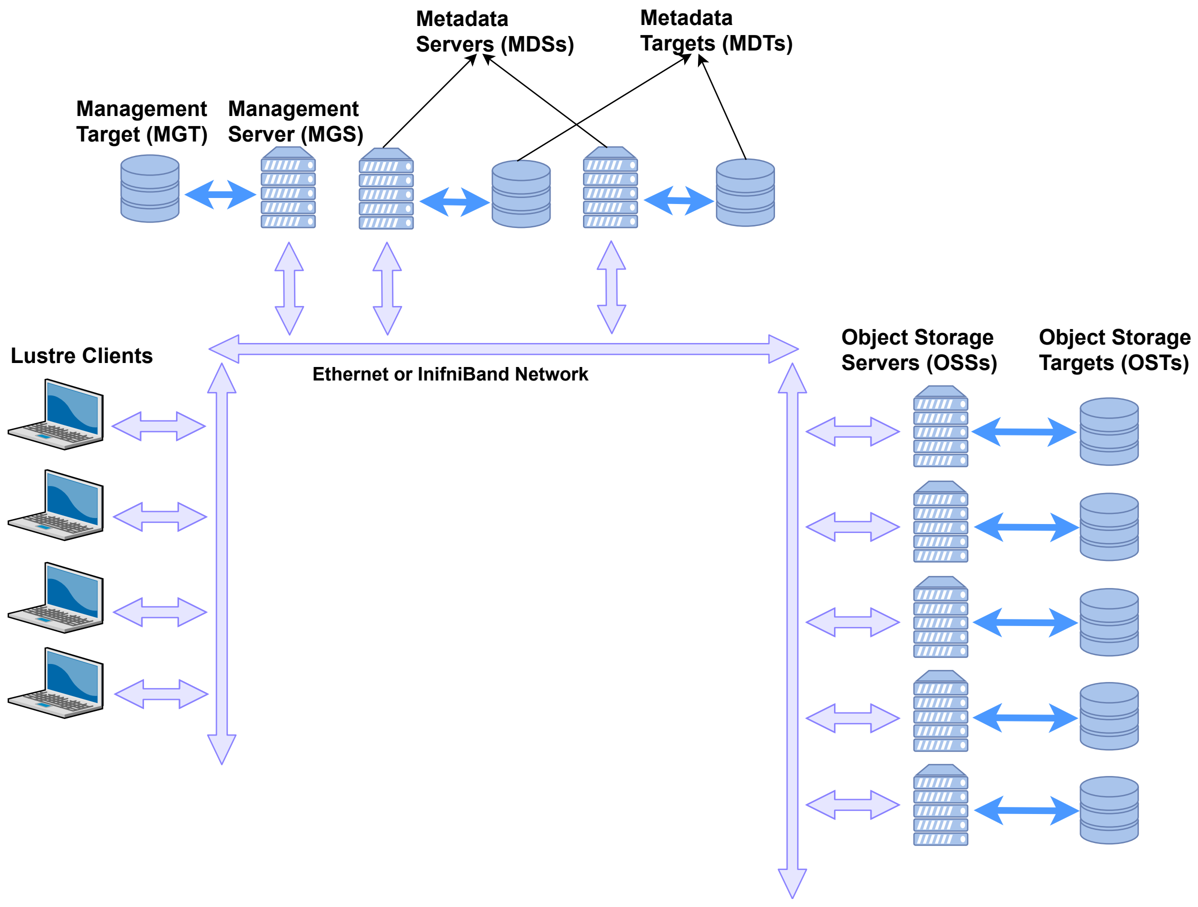


Figure 1. Lustre file system components in a basic cluster

1.4 Lustre File Layouts

Lustre stores file data by splitting the file contents into chunks and then storing those chunks across the storage targets. By spreading the file across multiple targets, the file size can exceed the capacity of any one storage target. It also allows clients to access parts of the file from multiple Lustre servers simultaneously, effectively scaling up the bandwidth of the file system. Users have the ability to control many aspects of the file’s layout by means of the `lfs setstripe` command, and they can query the layout for an existing file using the `lfs getstripe` command.

File layouts fall into one of two categories:

1. Normal / RAID0 - File data is striped across multiple OSTs in a round-robin manner.

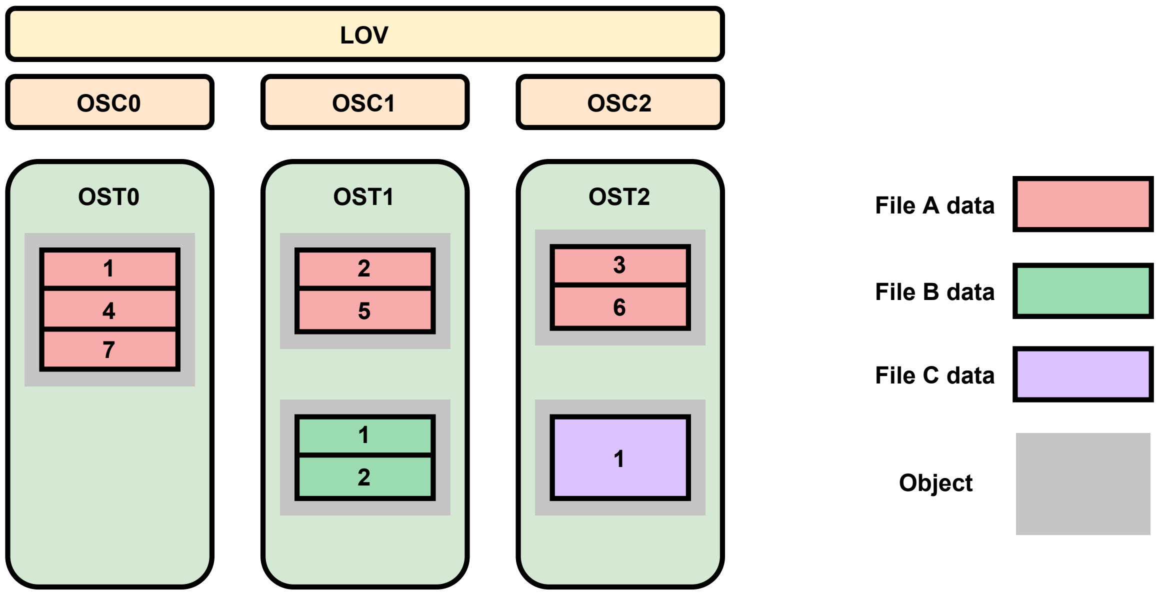


Figure 2. Normal RAID0 file striping in Lustre

2. Composite - Complex layouts that involve several components with potentially different striping patterns.

1.4.1 Normal (RAID0) Layouts

A normal layout is characterized by a stripe count and a stripe size. The stripe count determines how many OSTs will be used to store the file data, while the stripe size determines how much data will be written to an OST before moving to the next OST in the layout. As an example, consider the file layouts shown in Figure 2 for a simple file system with 3 OSTs residing on 3 different OSS nodes [*]. Note that Lustre indexes the OSTs starting at zero.

File A has a stripe count of three, so it will utilize all OSTs in the file system. We will assume that it uses the default Lustre stripe size of 1MB. When File A is written, the first 1MB chunk gets written to OST0. Lustre then writes the second 1MB chunk of the file to OST1 and the third chunk to OST2. When the file exceeds 3 MB in size, Lustre will round-robin back to the first allocated OST and write the fourth 1MB chunk to OST0, followed by OST1, etc. This illustrates how Lustre writes data in a RAID0 manner for a file. It should be noted that although File A has three chunks of data on OST0 (chunks #1, #4, and #7), all these chunks reside in a single object on the backend file system. From Lustre's point of view, File A consists of three objects, one per OST. Files B and C show layouts with the default Lustre stripe count of one, but only File B uses the default stripe size of 1MB. The layout for File C has been modified to use a larger stripe size of 2MB. If both File B and File C are 2MB in size, File B will be treated as two consecutive chunks written to the same OST whereas File C will be treated as a single chunk. However, this difference is mostly irrelevant since both files will still consist of a single 2MB object on their respective OSTs.

[*] Ignore the LOV and OSC components for the moment. These are client-related pieces that will not be discussed at this point.

1.4.2 Composite Layouts

A composite layout consists of one or more components each with their own specific layout. The most basic composite layout is a Progressive File Layout (PFL). Using PFL, a user can specify the same parameters used for a normal RAID0 layout but additionally specify a start and end point for that RAID0 layout. A PFL can be viewed as an array of normal layouts each of which covers a consecutive non-overlapping region of the file. PFL allows the data placement to change as the file increases in size, and because Lustre uses delayed instantiation, storage for subsequent components is allocated only when needed. This is particularly useful for increasing the stripe count of a file as the file grows in size.

The concept of a PFL has been extended to include two other layouts: Data on MDT (DoM) and Self Extending Layout (SEL). A DoM layout is specified just like a PFL except that the first component of the file resides on the same MDT as the file's metadata. This it typically used to store small amounts of data for quick access. A SEL is just like a PFL with the addition that an extent size can be supplied for one or more of the components. When a component is instantiated, Lustre only instantiates part of the component to cover the extent size. When this limit is exceeded, Lustre examines the OSTs assigned to the component to determine if any of them are running low on space. If not, the component is extended by the extent size. However, if an OST does run low on space, Lustre can dynamically shorten the current component and choose a different set of OSTs to use for the next component of the layout. This can safeguard against full OSTs that might generate a `ENOSPC` error when a user attempts to append data to a file.

Lustre has a feature called File Level Redundancy (FLR) that allows a user to create one or more mirrors of a file, each with its own specific layout (either normal or composite). When the file layout is inspected using `lfs getstripe`, it appears like any other composite layout. However, the `lcme_mirror_id` field is used to identify which mirror each component belongs to.

1.4.3 Distributed Namespace

The metatdata for the root of the Lustre file system resides on the primary MDT. By default, the metadata for newly created files and directories will reside on the same MDT as that of the parent directory, so without any configuration changes, the metadata for the entire file system would reside on a single MDT. In recent versions, a featured called Distributed Namespace (DNE) was added to allow Lustre to utilize multiple MDTs and thus scale up metadata operations. DNE was implemented in multiple phases, and DNE Phase 1 is referred to as Remote Directories. Remote Directories allow a Lustre administrator to assign a new subdirectory to a different MDT if its parent directory resides on MDT0. Any files or directories created in the remote directory also reside on the same MDT as the remote directory. This creates a static fan-out of directories from the primary MDT to other MDTs in the file system. While this does allow Lustre to spread overall metadata operations across mutliple servers, operations with any single directory are still constrained by the performance of a single MDS node. The static nature also prevents any sort of dynamic load balancing across MDTs.

DNE Phase 2, also known as Striped Directories, removed some of these limitations. For a striped directory, the metadata for all files and subdirectories contained in that directory are spread across multiple MDTs. Similar to how a file layout contains a stripe count, a striped directory also has a stripe count. This determines how many MDTs will be used to spread out the metadata. However, unlike file layouts which spread data across OSTs in a round-robin manner, a striped directory uses a hash function to calculate the MDT where the metadata should be placed. The upcoming DNE Phase 3 expands upon the ideas in DNE Phase 2 to support the creation of auto-striped directories. An auto-striped directory will start with a stripe count of 1 and then dynamically increase the stripe count as the number of files/subdirectories in that directory grows. Users can then utilize striped directories without knowing a priori how big the directory might become or having to worry about choosing a directory stripe count that is too low or too high.

1.4.4 File Identifiers and Layout Attributes

Lustre identifies all objects in the file system through the use of File Identifiers (FIDs). A FID is a 128-bit opaque identifier used to uniquely reference an object in the file system in much the same way that ext4 uses inodes or ZFS uses dnodes. When a user accesses a file, the filename is used to lookup the correct directory entry which in turn provides the FID for the MDT object corresponding to that file. The MDT object contains a set of extended attributes, one of which is called the Layout Extended Attribute (or Layout EA). This Layout EA acts as a map for the client to determine where the file data is actually stored, and it contains a list of the OSTs as well as the FIDs for the objects on those OSTs that hold the actual file data. Figure 3 shows an example of accessing a file with a normal layout of stripe count 3.

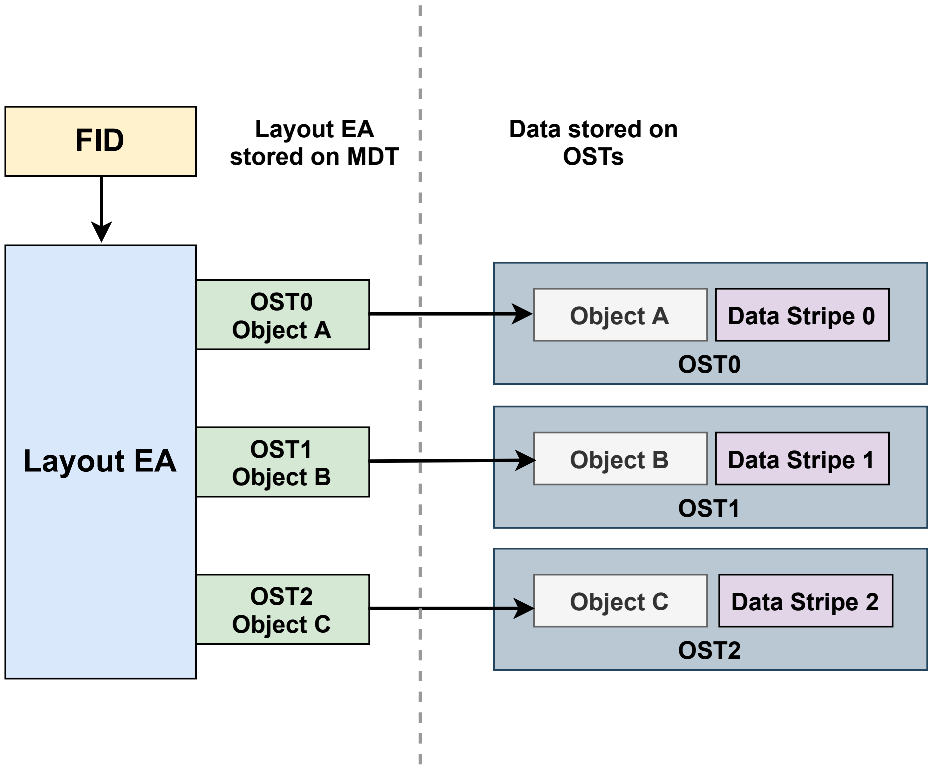


Figure 3. Using FID to access a file's Layout EA and corresponding OST objects

1.5 Lustre Software Stack

The Lustre software stack is composed of several different layered components. To provide context for more detailed discussions later, a basic diagram of these components is illustrated in Figure 4[†]. The arrows in this diagram represent the flow of a request from a client to the Lustre servers. System calls for

[†]There are more interactions between components than are shown in the diagram, but this simplified view is presented in order to illustrate some of the key interactions.

operations like read and write go through the Linux Virtual File System (VFS) layer to the Lustre LLITE layer which implements the necessary VFS operations. If the request requires metadata access, it is routed to the Logical Metadata Volume (LMV) that acts as an abstraction layer for the Metadata Client (MDC) components. There is a MDC component for each MDT target in the file system. Similarly, requests for data are routed to the Logical Object Volume (LOV) which acts as an abstraction layer for all of the Object Storage Client (OSC) components. There is an OSC component for each OST target in the file system. Finally, the requests are sent to the Lustre servers by first going through the Portal RPC (PTL-RPC) subsystem and then over the wire via the Lustre Networking (LNet) subsystem.

Requests arriving at the Lustre servers follow the reverse path from the LNet subsystem up through the PTL-RPC layer, finally arriving at either the OSS component (for data requests) or the MDS component (for metadata requests). Both the OSS and MDS components are multi-threaded and can handle requests for multiple storage targets (OSTs or MDTs) on the same server. Any locking requests are passed to the Lustre Distributed Lock Manager (LDLM). Data requests are passed to the OBD Filter Device (OFD) and then to the Object Storage Device (OSD). Metadata requests go from the MDS straight to the OSD. In both cases, the OSD is responsible for interfacing with the backend file system (either ldiskfs or ZFS) through the Linux VFS layer.

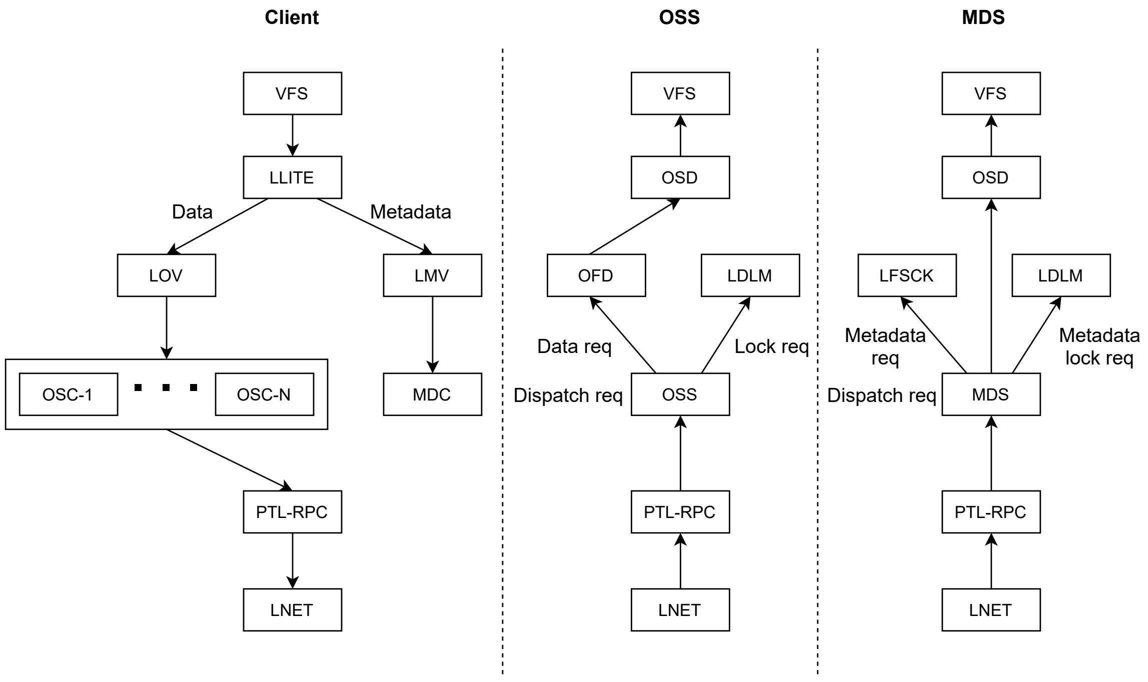


Figure 4. Basic view of Lustre software stack

Figure 5 provides a simple illustration of the interactions in the Lustre software stack for a client requesting file data. The Portal RPC and LNet layers are represented by the arrows showing communications between the client and the servers. The client begins by sending a request through the MDC to the MDS to open the file. The MDS server responds with the Layout EA for the file. Using this information, the client can determine which OST objects hold the file data and send requests through the LOV/OSC layer to the OSS servers to access the data.

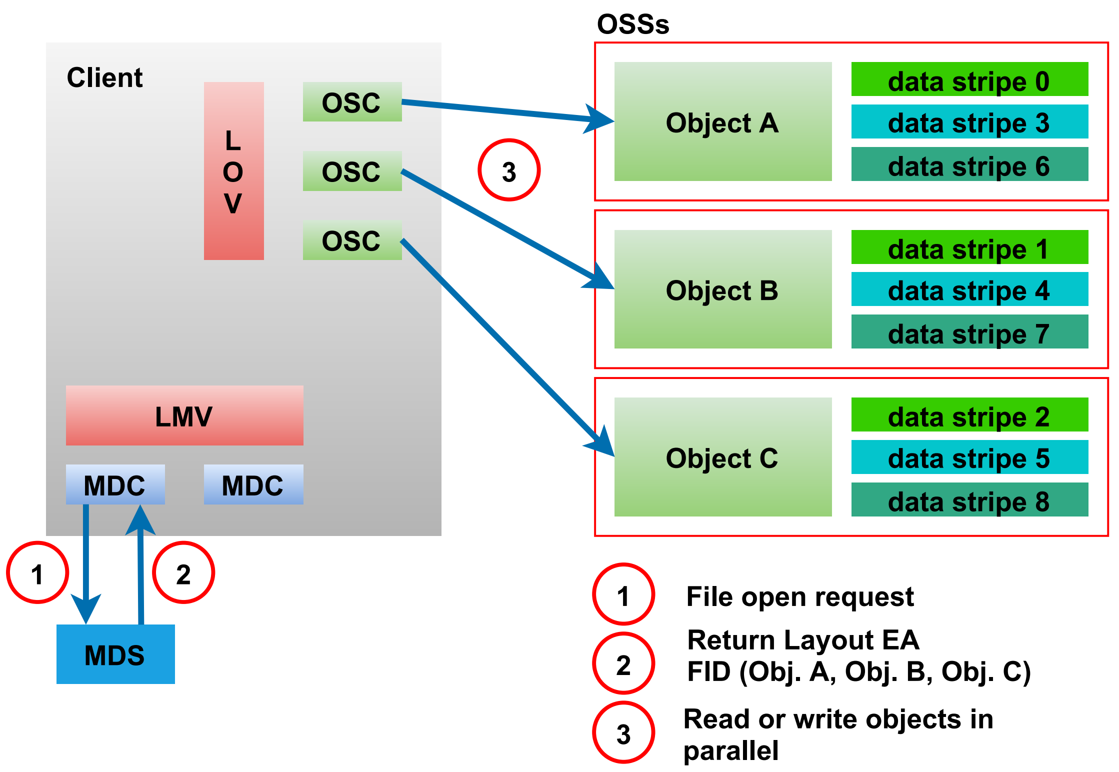


Figure 5. Lustre I/O operation: Lustre client requesting file data.

1.6 Detailed Discussion of Lustre Components

The descriptions of key Lustre concepts provided in this overview are intended to provide a basis for the more detailed discussion in subsequent Chapters. The remaining Chapters dive deeper into the following topics:

- Chapter 2. (Tests): Describes the testing framework used to test Lustre functionality and detect regressions.
- Chapter 3. (Utils): Covers command line utilities used to format and configure a Lustre file systems as well as user tools for setting file striping parameters.
- Chapter 4. (MGC): Discusses the MGC subsystem responsible for communications between Lustre nodes and the Lustre management server.
- Chapter 5. (Obdclass): Discusses the obdclass subsystem that provides an abstraction layer for other Lustre components including MGC, MDC, OSC, LOV, and LMV.
- Chapter 6. (Libcfs): Covers APIs used for process management and debugging support.
- Chapter 7. (File Identifiers, FID Location Database, and Object Index): Explains how object identifiers are generated and mapped to data on the backend storage.

This document extensively references parts of Lustre source code maintained by open source community [4].

2. TESTS

This chapter describes various tests and testing frameworks used to test Lustre functionality and performance.

2.1 Lustre Test Suites

Lustre Test Suites (LTS) is the largest collection of tests used to test Lustre file system. LTS consists of over 1600 tests, organized by their purpose and function. It is mainly composed of bash scripts, C programs and external applications. LTS provides various utilities to create, start, stop and execute tests. LTS can be used to execute test process automatically or in discrete steps. Using LTS the test process can be run as a group of tests or individual tests. LTS also allows to experiment with configurations and features such as ldiskfs, ZFS, DNE and HSM (Hierarchical Storage Manager). Tests in LTS are located in `/lustre/tests` directory in Lustre source tree and the major components in the test suite are given in Table 3.

Table 3. Lustre Test Suite components

Name	Description
`auster`	`auster` is used to run the Lustre tests. It can be used to run groups of tests, individual tests, or sub-tests. It also provides file system setup and cleanup capabilities.
`acceptance-small.sh`	The `acceptance-small.sh` script is a wrapper around `auster` that runs the test group `'regression'` unless tests are specified on the command line.
`functions.sh`	The `functions.sh` script provides functions for `run_*.sh` tests such as `run_dd.sh` or `run_dbench.sh`.
`test-framework.sh`	The `test-framework.sh` provides the fundamental functions needed by tests to create, setup, verify, start, stop, and reformat a Lustre file system.

2.2 Terminology

In this Section we describe relevant terminology related to Lustre Test Suites. All scripts and applications packaged as part of the `lustre-tests-*.rpm` and `lustre-iokit-*.rpm` are termed as Lustre Test Suites. The individual suites of tests contained in `/usr/lib64/lustre/tests` directory are termed as Test Suite. An example test suite is `sanity.sh`. A test suite is composed of Individual Tests. An example of an individual test is `test 4` from `large-lun.sh` test suite. Test suites can be bundled into a group for back-to-back execution (e.g. `regression`). Some of the LTS test examples include - Regression (`sanity, sanityn`), Feature Specific (`sanity-hsm, sanity-lfsck, ost-pools`), Configuration (`conf-sanity`), Recovery and Failures (`recovery-small, replay-ost-single`) and so on. Some of the active Lustre unit, feature and regression tests and their short description are given in Table 4.

2.3 Testing Lustre Code

When programming with Lustre, the best practices for testing are test often and test early in the development cycle. Before submitting the code changes to Lustre source tree, developer must ensure that the code passes acceptance-small test suite. To create a new test case, first find the bug that reproduces an

Table 4. Lustre unit, feature and regression tests

Name	Description
`conf-sanity`	A set of unit tests that verify the configuration tolls, and runs Lustre with multiple different setups to ensure correct operation in unusual system configurations.
`insanity`	A set of tests that verify the multiple concurrent failure conditions.
`large-scale`	Large scale tests that verify version based recovery features.
`metadata-updates`	Tests that metadata updates are properly completed when multiple clients delete files and modify the attributes of files.
`parallel-scale`	Runs functional tests, performance tests (e.g. IOR), and a stress test (`simul`).
`posix`	Automates POSIX compliance testing. Assuming that the POSIX source is already installed on the system, it sets up loop back ext4 file system, then install, build and run POSIX binaries on ext4. Then runs POSIX again on Lustre and compares results from ext4 and Lustre.
`recovery-small`	A set of unit tests that verify RPC replay after communications failure.
`runtests`	Simple basic regression tests that verify data persistence across write, unmount, and remount. This is one of the few tests that verifies data integrity across a full file system shutdown and remount, unlike many tests which at most only verify the existence/size of files.
`sanity`	A set of regression tests that verify operation under normal operating conditions. This tests a large number of unusual operations that have previously caused functional or data correctness issues with Lustre. Some of the tests are Lustre specific, and hook into the Lustre fault injection framework using `lctl set_param fail_loc=X` command to activate triggers in the code to simulate unusual operating conditions that would otherwise be difficult or impossible to simulate.
`sanityn`	Tests that verify operations from two clients under normal operating conditions. This is done by mounting the same file system twice on a single client, in order to allow a single script/program to execute and verify file system operations on multiple "clients" without having to be a distributed program itself.

issue, fix the bug and then verify the fixed code passes the existing tests. This means that the newly found bug/defect is not covered by the test cases from the test suite. After making sure that any of the existing test cases do not cover the new defect, a new test case can be introduced to exclusively test the bug.

2.3.1 Bypassing Failures

While testing Lustre, if one or more test cases are failing due to an issue not related to the bug that is currently being fixed, bypass option is available for the failing tests. For e.g., to skip `sanity.sh` sub-tests 36g and 65 and all of `insanity.sh` set the environment as,

```
export SANITY_EXCEPT="36g 65"
export INSANITY=no
```

A single line command can also be used to skip these tests when running `acceptance-small` test, as shown below.

```
SANITY_EXCEPT="36g 65" INSANITY=no ./acceptance-small.sh
```

2.3.2 Test Framework Options

The examples below show how to run a full test or sub-tests from the `acceptance-small` test suite.

- Run all tests in a test suite with the default setup.

  ```
  cd lustre/tests
  sh ./acceptance-small.sh
  ```

- Run only `recover-small` and `conf-sanity` tests from `acceptance-small` test suite.

  ```
  ACC_SM_ONLY="recovery-small conf-sanity" sh ./acceptance-small.sh
  ```

- Run only tests 1, 3 and 4 from `sanity.sh`.

  ```
  ONLY="1 3 4" sh ./sanity.sh
  ```

- skip tests 1 to 30 and run remaining tests in `sanity.sh`.

  ```
  EXCEPT="`seq 1 30`" sh sanity.sh
  ```

Lustre provides flexibility to easily add new tests to any of its test scripts.

Table 5. Tests in acceptance-small test suite

Name	Description
RUNTESTS	This is a basic regression test with unmount/remount.
SANITY	Verifies Lustre operation under normal operating conditions.
DBENCH	Dbench benchmark for simulating N clients to produce the file system load.
SANITYN	Verifies operations from two clients under normal operating conditions.
LFSCK	Tests e2fsck and lfsck to detect and fix file system corruption.
LIBLUSTRE	Runs a test linked to a liblustre client library.
CONF_SANITY	Verifies various Lustre configurations (including wrong ones), where the system must behave correctly.
RECOVERY_SMALL	Verifies RPC replay after a communications failure (message loss).
INSANITY	Tests multiple concurrent failure conditions.

2.4 Acceptance Small (acc-sm) Testing on Lustre

`acceptance small (acc-sm)` testing for Lustre is used to catch bugs in the early development cycles [6]. The `acceptance-small.sh` test scripts are located in the `lustre/tests` directory. `acc-sm` test suite contains three branches - `b1_6` branch (18 tests), `b1_8_gate` branch (28 tests), and `HEAD` branch (30 tests). The functionality of some of the commonly used tests in `acc-sm` suite is listed in Table 5. The order in which tests need to be executed is defined in the `acceptance-small.sh` script and in each test script.

2.5 Lustre Tests Environment Variables

This Section describes environment variables used to drive the Lustre tests. The environment variables are typically stored in a configuration script in `lustre/tests/cfg/$NAME.sh`, accessed by `NAME=name` environment variable within the test scripts. The default configuration for a single-node test is `NAME=local`, which accesses the `lustre/tests/cfg/local.sh` configuration file. Some of the important environment variables and their purpose for Lustre cluster configuration are listed in Table 6.

Table 6. Lustre tests environment variables

Variable	Purpose	Typical Value
`mds_HOST`	The network hostname of the primary MDS host. Uses local host name if unset.	`mdsnode-1`
`ost_HOST`	The network hostname of the primary OSS host. Uses local host name if unset.	`ossnode-1`
`mgs_HOST`	The network hostname of the primary MGS host. Uses `$mds_HOST` if unset.	`mgsnode`
`CLIENTS`	A comma separated list of the clients to be used for testing.	`client-1, client-2, client-3`
`RCLIENTS`	A comma separated list of the remote clients to be used for testing. One client actually executes the test framework, the other clients are remote clients.	`client-1, client-3` (which would imply that `client-2` is actually running the test framework.)
`NETTYPE`	The network infrastructure to be used in LNet notation.	`tcp` or `o2ib`
`mdsfailover_HOST`	If testing high availability, the hostname of the backup MDS that can access the MDT storage.	`mdsnode-2`
`ostfailover_HOST`	If testing high availability, the hostname of the backup OSS that can access the OST storage.	`ossnode-2`
`MDSCOUNT`	Number of MDTs to use (valid for Lustre 2.4 and later).	`1`
`MDSSIZE`	The size of the MDT storage in kilobytes. This can be smaller than the MDT block device, to speed up testing. Use the block device size if unspecified or equal to zero.	`200000`
`MGSNID`	LNet Node ID if it does not map to the primary address of `$mgs_HOST` for `$NETTYPE`.	`$mgs_HOST`

`MGSSIZE`	The size of the MGT stoarge in kilobytes, if it is separate from the MDT device. This can be smaller than the MGT block device, to speed up testing. Use the block device size if unspecified or equal to zero.	`16384`
`REFORMAT`	Whether the file system will be reformatted between tests.	`true`
`OSTCOUNT`	The number of OSTs that are being provided by the OSS on `$ost_HOST`.	`1`
`OSTSIZE`	Size of the OST storage in kilobytes. Can be smaller than the OST block device, to speed up testing. Use the block device size if unspecified or equal to zero.	`1000000`
`FSTYPE`	File system type to use for all OST and MDT devices.	`ldiskfs`, `zfs`
`FSNAME`	The Lustre file system name to use for testing. Uses `lustre` by default.	`testfs`
`MOUNT`	Mount point to use for the client test file system(s). Defaults to `/mnt/$FSNAME` if unspecified.	`/mnt/testfs`
`DIR`	Directory in which to run the Lustre tests. Must be within the mount point specified by `$MOUNT`. Defaults to `$MOUNT` if unspecified.	`$MOUNT`
`TIMEOUT`	Lustre timeout to use during testing, in seconds. Reduced from the default to speed testing.	`20`
`PDSH`	The parallel shell command to use for running shell operations on one or more remote hosts.	`pdsh -w nodes[1-5]`
`MPIRUN`	Command to use for launching MPI test programs.	`mpirun`

3. UTILS

3.1 Introduction

The administrative utilities provided with Lustre software allow to set up Lustre file system in different configurations. Lustre utilities provide a wide range of configuration options for creating a file system on a block device, scaling Lustre file system by adding additional OSTs or clients, changing stripe layout for data etc. Examples of some Lustre utilities include,

- `mkfs.lustre` - This utility is used to format a disk for a Lustre service.
- `tunefs.lustre` - This is used to modify configuration information on a Lustre target disk.
- `lctl` - `lctl` is used to control Lustre features via ioctl interfaces, including various configuration, maintenance and debugging features.
- `mount.lustre` - This is used to start Lustre client or server on a target.

- `lfs` - `lfs` is used for configuring and querying options related to files.

In the following Sections we describe various user utilities and system configuration utilities in detail.

3.2 User Utilities

In this section we describe a few important user utilities provided with Lustre [1].

3.2.1 lfs

`lfs` can be used for configuring and monitoring Lustre file system. Some of most common uses of `lfs` are, create a new file with a specific striping pattern, determine default striping pattern, gather extended attributes for specific files, find files with specific attributes, list OST information and set quota limits. Some of the important `lfs` options are shown in Table 7.

Table 7. lfs utility options

Option	Description
`changelog`	`changelog` can show the metadata changes happening on MDT. Users can also specify start and end points of the changelog as optional arguments.
`df`	`df` reports the usage of all mounted Lustre file systems. For each Lustre target UUID (Universally Unique Identifier), used and available space on the targets, and mount point are reported. The `path` option allows users to specify a file system path and if specified df reports usage for the specified file system.
`find`	`find` searches the directory tree rooted at the given directory/file path name for files that match the specified parameters. `find` can also have various options such as `--atime`, `--mtime`, `--type`, `--user` etc. For example `--atime` allows to find files based on last accessed time, similarly `--mtime` allows to find files based on last modified time.
`getstripe`	`getstripe` obtains and lists striping information for the specified filename or directory. By default, the stripe count, stripe size, pattern, stripe offset, and OST indices and their IDs are returned. For composite layout files all the above fields are displayed for all the components in the layout.
`setstripe`	`setstripe` allows users to create new files with a specific file layout/stripe pattern configuration. Note that changing the stripe layout of an existing file is not possible using `setstripe`.

A few examples on the usage of lfs utility is shown below.

- Create a file name `file1` striped on three OSTs with 32KB on each stripe

```
$ lfs setstripe -s 32k -c 3 /mnt/lustre/file1
```

- Show the default stripe pattern on a given directory (`dir1`).

```
$ lfs getstripe -d /mnt/lustre/dir1
```

- List detailed stripe allocation for a give `file, file2`.

```
lfs getstripe -v /mnt/lustre/file2
```

3.2.2 lfs _migrate

The `lfs_migrate` utility is used to migrate file data between Lustre OSTs. This utility does the migration in two steps. It first copies the specified files to set of temporary files. This can be performed using `lfs setstripe` options, if specified. It can also optionally verify if the file contents have changed or not. The second step is to then swap the layout between the temporary file and the original file (or even renaming the temporary file to the original filename). `lfs_migrate` is a tool that helps users to balance or manage space usage among Lustre OSTs.

3.2.3 lctl

The `lctl` utility is used for controlling and configuring Lustre file system. `lctl` allows the following capabilities - control Lustre via an ioctl interface, setup Lustre in various configurations, and access debugging features of Lustre. Issuing `lctl` command on Lustre client gives a prompt that allows to execute `lctl` sub-commands. Some of the common commands associated with `lctl` are `dl, device, network up/down, list_nids, ping nid, and conn_list`.

To get help with `lctl` commands `lctl help` <COMMAND> or `lctl --list-commands` can be used.

Another important use of `lctl` command is accessing Lustre parameters. `lctl get, set_param` provides a platform-independent interface to the Lustre tunables. When the file system is running, `lctl set_param` command can be used to set parameters temporarily on the affected nodes. The syntax of this command is,

```
lctl set_param [-P] [-d] obdtype.obdname.property=value
```

In this command, `-P` option is used to set parameters permanently, `-d` deletes permanent parameters. To obtain current Lustre parameter settings, `lctl get_param command` can be used on the desired node. For example,

```
lctl get_param [-n] obdtype.obdname.parameter
```

Some of the common commands associated with `lctl` and their description are shown in Table 8.

3.2.4 llog_reader

The `llog_reader` utility translates a Lustre configuration log into human-readable form. The syntax of this utility is,

```
llog_reader filename
```

Table 8. lctl utility options

Option	Description
`dl`	Shows all the local Lustre OBD devices.
`list_nids`	Prints all NIDs (Network Identifiers) on the local node. LNet must be running to execute this command.
`ping nid`	Checks the LNet layer connectivity between Lustre components via an LNet ping. This can use LNet fabric such as TCP or IB.
`network up | down`	Starts or stops LNet, or selects a network type for other `lctl` LNet commands.
`device` *`devname`*	Selects the specified OBD device. All subsequent commands depend on the device being set.
`conn_list`	Prints all the connected remote NIDs for a given network type.

`llog_reader` reads and parses the binary formatted Lustre's on-disk configuration logs. To examine a log file on a stopped Lustre server, mount its backing file system as `ldiskfs` or `zfs`, then use `llog_reader` to dump the log file's contents. For example,

```
mount -t ldiskfs /dev/sda /mnt/mgs
llog_reader /mnt/mgsCONFIGS/tfs-client
```

This utility can also be used to examine the log files when Lustre server is running. The ldiskfs-enabled `debugfs` utility can be used to extract the log file, for example,

```
debugfs -c -R 'dump CONFIGS/tfs-client /tmp/tfs-client' /dev/sds
llog_reader /tmp/tfs-client
```

3.2.5 mkfs.lustre

The `mkfs.lustre` utility is used to format a Lustre target disk. The syntax of this utility is,

```
mkfs.lustre target_type [options] device
```

where `target_type` can be OST, MDT, networks to which to restrict this OST/MDT and MGS. After formatting, the disk using `mkfs.lustre`, it can be mounted to start the Lustre service. Two important options that can be specified along with this command are `--backfstype=fstype` and `--fsname=filesystem_name`. The former forces a particular format for the backing file system such as `ldiskfs` (default) or `zfs` and the later specifies the Lustre file system name of which the disk is part of (default name for file system is `lustre`).

3.3 mount.lustre

The `mount.lustre` utility is used to mount the Lustre file system on a target or client. The syntax of this utility is,

```
mount -t lustre [-o options] device mountpoint
```

After mounting users can use the Lustre file system to create files/directories and execute several other Lustre utilities on the file system. To unmount a mounted file system the `umount` command can be used as shown below.

```
umount device mountpoint
```

Some of the important options used along with this utility are discussed below with the help of examples.

- The following `mount` command mounts Lustre on a client at the mount point `/mnt/lustre` with MGS running on a node with nid `10.1.0.1@tcp`.

  ```
  mount -t lustre 10.1.0.1@tcp:/lustre /mnt/lustre
  ```

- To start the Lustre metadata service from `/dev/sda` on a mount point `/mnt/mdt` the following command can be used.

  ```
  mount -t lustre /dev/sda /mnt/mdt
  ```

3.4 tunefs.lustre

The `tunefs.lustre` utility is used to modify configuration information on a Lustre target disk. The syntax of this utility is,

```
tunefs.lustre [options] /dev/device
```

However the tunefs utility does not reformat the disk or erase the contents on the disk. The parameters specified using tunefs are set in addition to the old parameters by default. To erase old parameters and use newly specified parameters, use the following options with tunefs.

```
tunefs.lustre --erase-params --param=new_parameters
```

4. MGC

4.1 Introduction

The Lustre client software involves primarily three components, management client (MGC), a metadata client (MDC), and multiple object storage clients (OSCs), one corresponding to each OST in the file system. Among this, the management client acts as an interface between Lustre virtual file system layer and Lustre management server (MGS). Lustre targets register with MGS to register information with MGS while Lustre clients contact MGS to retrieve information from it.

The major functionalities of MGC are Lustre log handling, Lustre distributed lock management and file system setup. MGC is the first obd device created in Lustre obd device life cycle. An obd device in Lustre provides a level of abstraction on Lustre components such that generic operations can be applied without knowing the specific devices you are dealing with. The remaining Sections in this Chapter describe MGC module initialization, various MGC obd operations and log handling in detail. In the following Sections we will be using the terms clients and servers to represent service clients and servers created to communicate between various components in Lustre. Whereas the physical nodes representing Lustre's clients and servers will be explicitly mentioned as 'Lustre clients' and 'Lustre servers'.

4.2 MGC Module Initialization

When the MGC module initializes, it registers MGC as an obd device type with Lustre using `class_register_type()` as shown in Source Code 1. Obd device data and metadata operations are defined using the `obd_ops` and `md_ops` structures respectively. Since MGC deals with metadata in Lustre, it has only `obd_ops` operations defined. However the metadata client (MDC) has both metadata and data operations defined since the data operations are used to implement Data on Metadata (DoM) functionality in Lustre. The `class_register_type()` function passes `&mgc_obd_ops`, `NULL`, `false`, `LUSTRE_MGC_NAME`, and `NULL` as its arguments. `LUSTRE_MGC_NAME` is defined as "`mgc`" in `include/obd.h`.

Source Code 1. class_register_type() function defined in obdclass/genops.c

```
int class_register_type(const struct obd_ops *dt_ops,
                        const struct md_ops *md_ops,
                        bool enable_proc, struct lprocfs_vars *vars,
                        const char *name, struct lu_device_type *ldt)
```

4.3 MGC obd Operations

MGC obd operations are defined by `mgc_obd_ops` structure as shown in Source Code 2. Note that all MGC obd operations are defined as function pointers. This type of programming style avoids complex switch cases and provides a level of abstraction on Lustre components such that the generic operations can be applied without knowing the details of specific obd devices.

Source Code 2. mgc_obd_ops structure defined in mgc/mgc_request.c

```
static const struct obd_ops mgc_obd_ops = {
        .o_owner          = THIS_MODULE,
        .o_setup          = mgc_setup,
        .o_precleanup     = mgc_precleanup,
        .o_cleanup        = mgc_cleanup,
        .o_add_conn       = client_import_add_conn,
        .o_del_conn       = client_import_del_conn,
        .o_connect        = client_connect_import,
        .o_disconnect     = client_disconnect_export,
        .o_set_info_async = mgc_set_info_async,
        .o_get_info         = mgc_get_info,
        .o_import_event = mgc_import_event,
        .o_process_config = mgc_process_config,
};
```

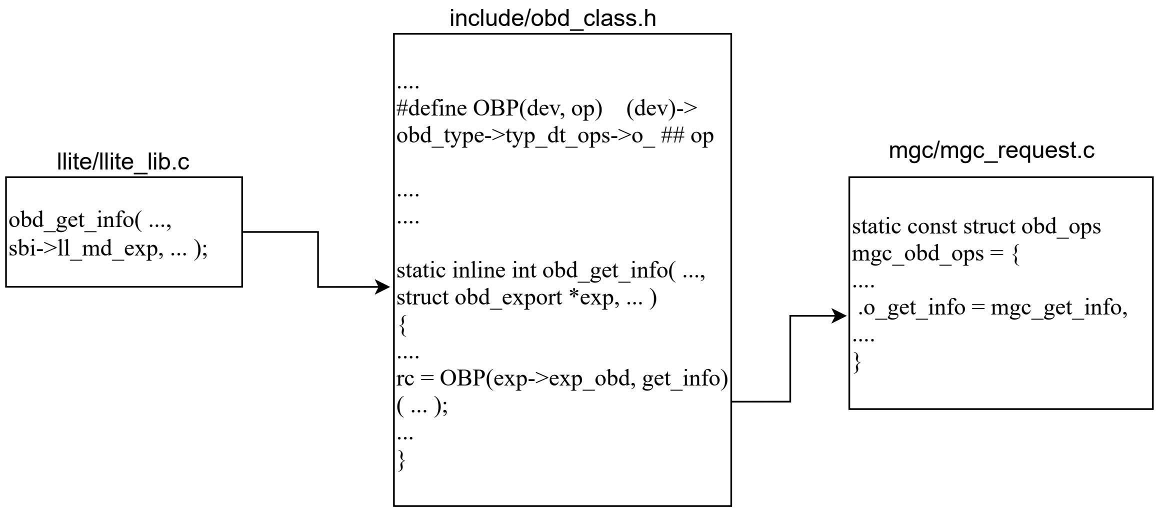
In Lustre one of the ways two subsystems share data is with the help of `obd_ops` structure. To understand how the communication between two subsystems work let us take an example of `mgc_get_info()` from the `mgc_obd_ops` structure. The subsystem llite makes a call to `mgc_get_info()` (in `llite/llite_lib.c`) by passing a key (`KEY_CONN_DATA`) as an argument. But notice that llite invokes `obd_get_info()` instead of `mgc_get_info()`. `obd_get_info()` is defined in `include/obd_class.h` as shown in Figure 6. We can see that this function invokes an `OBP` macro by passing an `obd_export` device structure and a `get_info` operation. The definition of this macro concatenates `o` with `op` (operation) so that the resulting function call becomes `o_get_info()`.

So how does llite make sure that this operation is directed specifically towards MGC obd device? `obd_get_info()` from `llite/llite_lib.c` has an argument called `sbi->ll_md_exp`. The `sbi` structure is a type of `ll_sb_info` defined in `llite/llite_internal.h` (refer Figure 7). And the `ll_md_exp` field from `ll_sb_info` is a type of `obd_export` structure defined in `include/lustre_export.h`. `obd_export` structure has a field `*exp_obd` which is an `obd_device` structure (defined in `include/obd.h`). Another MGC obd operation `obd_connect()` retrieves export using the `obd_device` structure. Two functions involved in this process are `class_name2obd()` and `class_num2obd()` defined in `obdclass/genops.c`.

In the following Sections we describe some of the important MGC obd operations in detail.

4.4 mgc_setup()

`mgc_setup()` is the initial routine that gets executed to start and setup the MGC obd device. In Lustre MGC is the first obd device that is being setup as part of the obd device life cycle process. To understand when `mgc_setup()` gets invoked in the obd device life cycle, let us explore the workflow from the Lustre module initialization.



```
obd_get_info( ...,
sbi->ll_md_exp, ... );
```

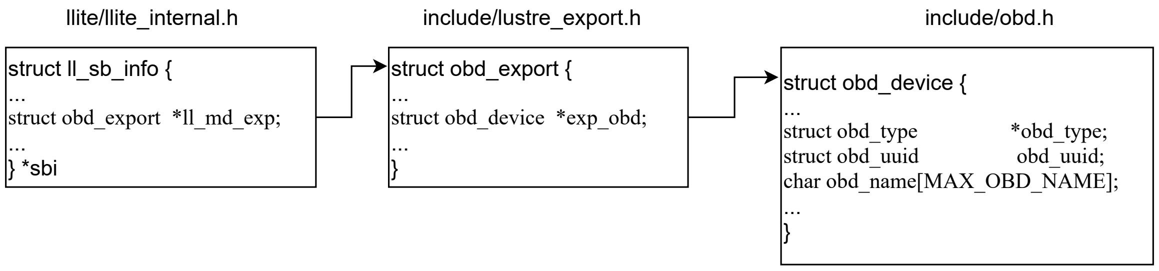
```
....
#define OBP(dev, op)    (dev)->
obd_type->typ_dt_ops->o_ ## op

....
....

static inline int obd_get_info( ...,
struct obd_export *exp, ... )
{
....
rc = OBP(exp->exp_obd, get_info)
( ... );
...
}
```

```
static const struct obd_ops
mgc_obd_ops = {
....
 .o_get_info = mgc_get_info,
....
}
```

Figure 6. Communication between llite and mgc through obdclass.



```
struct ll_sb_info {
...
struct obd_export  *ll_md_exp;
...
} *sbi
```

```
struct obd_export {
...
struct obd_device  *exp_obd;
...
}
```

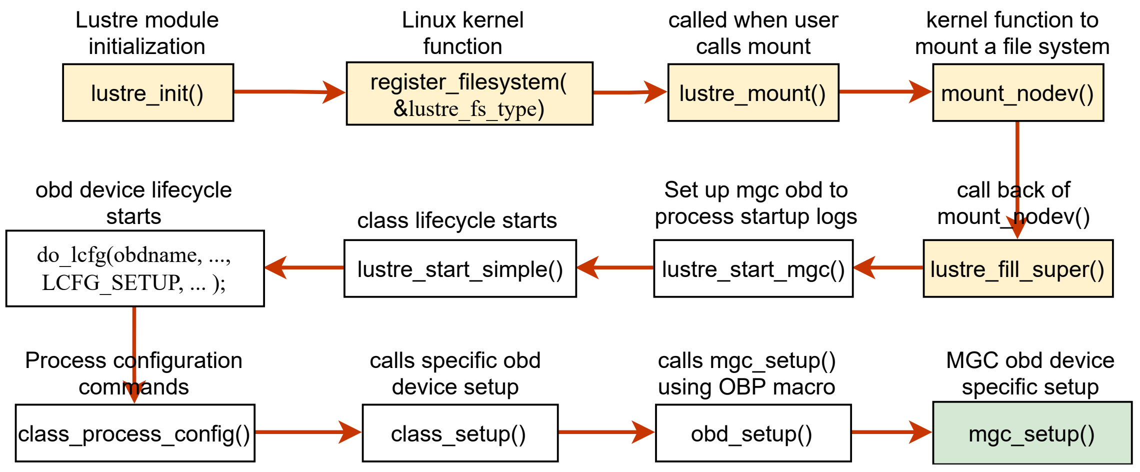
```
struct obd_device {
...
struct obd_type              *obd_type;
struct obd_uuid               obd_uuid;
char obd_name[MAX_OBD_NAME];
...
}
```

Figure 7. Data structures involved in the communication between mgc and llite subsystems.

The Lustre module initialization begins from the `lustre_init()` routine defined in `llite/super25.c` (shown in Figure 8). This routine is invoked when the `'lustre'` module gets loaded. `lustre_init()` invokes `register_filesystem(&lustre_fs_type)` which registers `'lustre'` as the file system and adds it to the list of file systems the kernel is aware of for mount and other syscalls. `lustre_fs_type` structure is defined in the same file as shown in Source Code 3.

When a user mounts Lustre, the `lustre_mount()` gets invoked as evident from this structure. `lustre_mount()` is defined in the same file and which in turn calls `mount_nodev()` routine. The `mount_nodev()` invokes its call back function `lustre_fill_super()` which is also defined in `llite/super25.c`. `lustre_fill_super()` is the entry point for the mount call from the Lustre client into Lustre.

`lustre_fill_super()` invokes `lustre_start_mgc()` defined in `obdclass/obd_mount.c`. This sets up the MGC obd device to start processing startup logs. The `lustre_start_simple()` routine called here starts the MGC obd device (defined in `obdclass/obd_mount.c`). `lustre_start_simple()` eventually leads to the invocation of obdclass specific routines `class_attach()` and `class_setup()` (described in detail in the Chapter 5.) with the help of a `do_lcfg()` routine that takes obd device name and a lustre configuration command (`lcfg_command`) as arguments. Various lustre configuration commands are `LCFG_ATTACH, LCFG_DETACH, LCFG_SETUP, LCFG_CLEANUP` and so on. These are defined in `include/uapi/linux/lustre/lustre_cfg.h` as shown in Source Code 4.



Lustre module initialization
lustre_init()
Linux kernel function
register_filesystem(&lustre_fs_type)
called when user calls mount
lustre_mount()
kernel function to mount a file system
mount_nodev()
call back of mount_nodev()
lustre_fill_super()
Set up mgc obd to process startup logs
lustre_start_mgc()
class lifecycle starts
lustre_start_simple()
obd device lifecycle starts
do_lcfg(obdname, ..., LCFG_SETUP, ...);
Process configuration commands
class_process_config()
calls specific obd device setup
class_setup()
calls mgc_setup() using OBP macro
obd_setup()
MGC obd device specific setup
mgc_setup()

Figure 8. mgc_setup() call graph starting from Lustre file system mounting.

The first `lcfg_command` that is being passed to `do_lcfg()` routine is `LCFG_ATTACH` which will result in the invocation of obdclass function `class_attach()`. We will describe `class_attach()` in detail in Chapter 5. The second `lcfg_command` passed to `do_lcfg()` function is `LCFG_SETUP` which will result in the invocation of `mgc_setup()` eventually. `do_lcfg()` calls `class_process_config()` (defined in `obdclass/obd_config.c`) and passes the `lcfg_command` that it received. In case of `LCFG_SETUP` command the `class_setup()` routine gets invoked. This is defined in the same file and its primary duty is to create hashes and self export and call obd device specific setup. The device specific setup call is in turn invoked through another routine called `obd_setup()`. `obd_setup()` is defined in `include/obd_class.h` as an inline function in the same way `obd_get_info()` is defined. `obd_setup()` calls the device specific setup routine with the help of the `OBP` macro (refer Section 4.3 and Figure 6). Here, in case of MGC obd device `mgc_setup()` defined as part of the `mgc_obd_ops` structure (shown in Source Code 2) gets invoked by the `obd_setup()` routine. Note that the yellow colored blocks in Figure 8 will be referenced again in Chapter 5. to illustrate the lifecycle of the MGC obd device.

Source Code 3. lustre_fs_type structure defined in llite/super25.c

```
static struct file_system_type lustre_fs_type = {
        .owner          = THIS_MODULE,
        .name           = "lustre",
        .mount          = lustre_mount,
        .kill_sb        = lustre_kill_super,
        .fs_flags       = FS_RENAME_DOES_D_MOVE,
};
```

Source Code 4. Lustre configuration commands defined in include/uapi/linux/lustre/lustre_cfg.h

```
enum lcfg_command_type {
        LCFG_ATTACH                = 0x00cf001, /**< create a new obd instance */
        LCFG_DETACH                = 0x00cf002, /**< destroy obd instance */
        LCFG_SETUP                 = 0x00cf003, /**< call type-specific setup */
        LCFG_CLEANUP               = 0x00cf004, /**< call type-specific cleanup
                                                  */
        LCFG_ADD_UUID              = 0x00cf005, /**< add a nid to a niduuid */
        . . . . .
};
```

4.4.1 Operation

`mgc_setup()` first adds a reference to the underlying Lustre PTL-RPC layer. Then it sets up an RPC client for the obd device using `client_obd_setup()` (defined in `ldlm/ldlm_lib.c`). Next `mgc_llog_init()` initializes Lustre logs which will be processed by MGC at the MGS server. These logs are also sent to the Lustre client and the client side MGC mirrors these logs to process the data. The tunable parameters persistently set at MGS are sent to MGC and Lustre logs processed at the MGC initializes these parameters. In Lustre the tunables have to be set before Lustre logs are processed and `mgc_tunables_init()` helps to initialize these tunables. Few examples of the tunables set by this function are `conn_uuid`, `uuid`, `ping` and `dynamic_nids` and can be viewed in `/sys/fs/lustre/mgc` directory by logging into any Lustre client. `kthread_run()` starts an `mgc_requeue_thread` which keeps reading the lustre logs as the entries come in. A flowchart showing the `mgc_setup()` workflow is shown in Figure 10.

4.5 Lustre Log Handling

Lustre extensively makes use of logging for recovery and distributed transaction commits. The logs associated with Lustre are called '`llogs`' and config logs, startup logs and change logs correspond to various kinds of `llogs`. As described in Chapter 3. Section 3.2.4, the `llog_reader` utility can be used to read these Lustre logs. When a Lustre target registers with MGS, the MGS constructs a log for the target.

Similarly, a `lustre-client` log is created for the Lustre client when it is mounted. When a user mounts the Lustre client, it triggers to download the Lustre config logs on the client. As described earlier MGC subsystem is responsible for reading and processing the logs and sending them to Lustre clients and Lustre servers.

4.5.1 Log Processing in MGC

The `lustre_fill_super()` routine described in Section 4.4 makes a call to `ll_fill_super()` function defined in `llite/llite_lib.c`. This function initializes a config log instance specific to the super block passed from `lustre_fill_super()`. Since the same MGC may be used to follow multiple config logs (e.g. ost1, ost2, Lustre client), the config log instance is used to keep the state for a specific log. Afterwards `lustre_fill_super()` invokes `lustre_process_log()` which gets a config log from MGS and starts processing it. `lustre_process_log()` gets called for both Lustre clients and Lustre servers and it continues to process new statements appended to the logs. It first resets and allocates `lustre_cfg_bufs` (which temporarily store log data) and calls `obd_process_config()` which eventually invokes the obd device specific `mgc_process_config()` (as shown in Figure 9) with the help of `OBP` macro. The `lcfg_command` passed to `mgc_process_config()` is `LCFG_LOG_START` which gets the config log from MGC, starts processing it and adds the log to list of logs to follow. `config_log_add()` defined in the same file accomplishes the task of adding the log to the list of active logs watched for updates by MGC. Few other important log processing functions in MGC are - `mgc_process_log` (that gets a configuration log from the MGS and processes it), `mgc_process_recover_nodemap_log` (called if the Lustre client was notified for target restarting by the MGS), and `mgc_apply_recover_logs` (applies the logs after recovery).

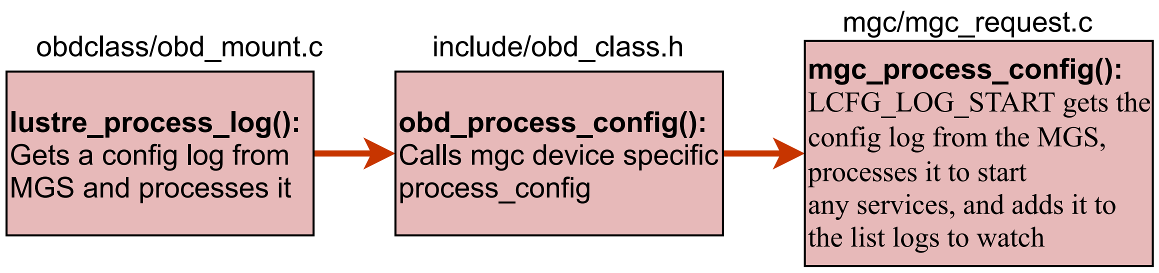

obdclass/obd_mount.c
lustre_process_log(): Gets a config log from MGS and processes it
include/obd_class.h
obd_process_config(): Calls mgc device specific process_config
mgc/mgc_request.c
mgc_process_config(): LCFG_LOG_START gets the config log from the MGS, processes it to start any services, and adds it to the list logs to watch

Figure 9. mgc_process_config() call graph

4.6 mgc_precleanup() and mgc_cleanup()

Cleanup functions are important in Lustre in case of file system unmounting or any unexpected errors during file system setup. The `class_cleanup()` routine defined in `obdclass/obd_config.c` starts the process of shutting down an obd device. This invokes `mgc_precleanup()` (through `obd_precleanup()`) which makes sure that all the exports are destroyed before shutting down the obd device. `mgc_precleanup()` first decrements the `mgc_count` that was incremented during `mgc_setup()`. The `mgc_count` keeps the count of the running MGC threads and makes sure not to shut down any threads prematurely. Next it waits for any requeue thread to gets completed and calls `obd_cleanup_client_import()`. `obd_cleanup_client_import()` destroys client side import interface of the obd device. Finally `mgc_precleanup()` invokes `mgc_llog_fini()` which cleans up the lustre logs associated with the MGC. The log cleaning is accomplished by `llog_cleanup()` routine defined in `obdclass/llog_obd.c`.

`mgc_cleanup()` function deletes the profiles for the last MGC obd using `class_del_profiles()` defined in `obdclass/obd_config.c`. When MGS sends a buffer of data to MGC, the lustre profiles helps to identify the intended recipients of the data. Next the `lprocfs_obd_cleanup()` routine (defined in `obdclass/lprocfs_status.c`) removes `sysfs` and `debugfs` entries for the obd device. It then decrements the reference to PTL-RPC layer and finally calls `client_obd_cleanup()`. This function (defined in `ldlm/ldlm_lib.c`) makes the obd namespace point to NULL, destroys the client side import interface and finally frees up the obd device using `OBD_FREE` macro. Figure 10 shows the workflows for both setup and cleanup routines in MGC parallely. The `class_cleanup()` routine defined in `obd_config.c` starts the MGC shut down process. Note that after the `obd_precleanup()`, `uuid-export` and `nid-export` hashtables are freed up and destroyed. `uuid-export` HT stores uuids for different obd devices where as `nid-export` HT stores ptl-rpc network connection information.

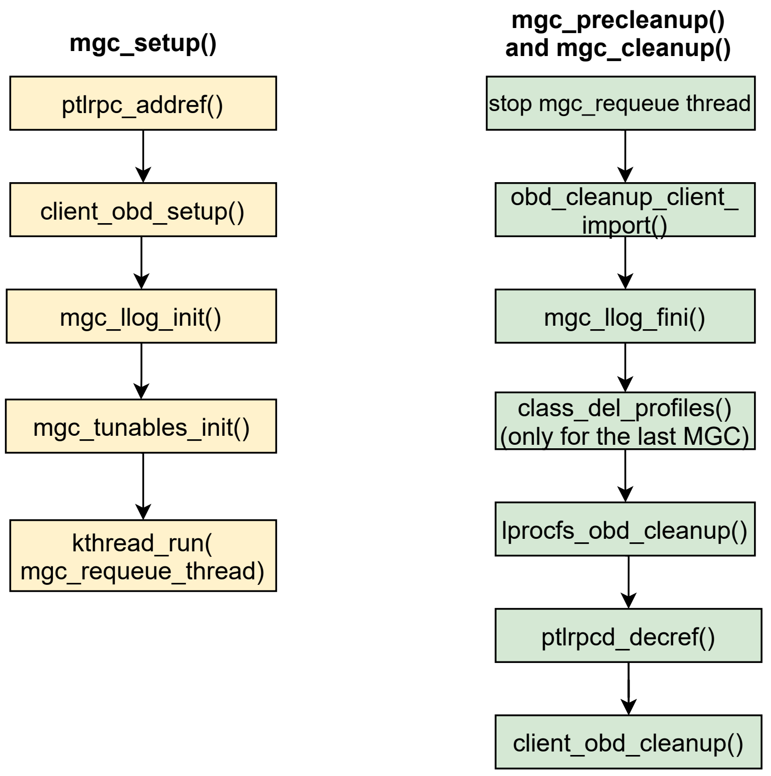


Figure 10. mgc_setup() vs. mgc_cleanup()

4.7 mgc_import_event()

The `mgc_import_event()` function handles the events reported at the MGC import interface. The type of import events identified by MGC are listed in `obd_import_event` enum defined in `include/lustre_import.h` as shown in Source Code 5. Client side imports are used by the clients to communicate with the exports on the server (for instance if MDS wants to communicate with MGS, MDS will be using its client import to communicate with MGS' server side export). More detailed description of import and export interfaces on obd device is given in Chapter 5.

Source Code 5. obd_import_event enum defined in include/lustre_import.h

```
enum obd_import_event {
        IMP_EVENT_DISCON     = 0x808001,
        IMP_EVENT_INACTIVE   = 0x808002,
        IMP_EVENT_INVALIDATE = 0x808003,
        IMP_EVENT_ACTIVE     = 0x808004,
        IMP_EVENT_OCD        = 0x808005,
        IMP_EVENT_DEACTIVATE = 0x808006,
        IMP_EVENT_ACTIVATE   = 0x808007,
};
```

Some of the remaining obd operations for MGC such as `client_import_add_conn()`, `client_import_del_conn()`, `client_connect_import()` and `client_disconnect_export()` will be explained in obdclass and ldlm Chapters.

5. OBDCLASS

5.1 Introduction

The obdclass subsystem in Lustre provides an abstraction layer that allows generic operations to be applied on Lustre components without having the knowledge of specific components. MGC, MDC, OSC, LOV, LMV are examples of obd devices in Lustre that make use of the obdclass generic abstraction layer. The obd devices can be connected in different ways to form client-server pairs for internal communication and data exchange in Lustre. Note that the client and server referred here are service clients and servers roles temporarily assumed by the obd devices but not physical nodes representing Lustre clients and Lustre servers.

Obd devices in Lustre are stored internally in an array defined in `obdclass/genops.c` as shown in Source Code 6. The maximum number of obd devices in Lustre per node is limited by `MAX_OBD_DEVICES` defined in `include/obd.h` (shown in Source Code 7). The obd devices in the `obd_devs` array are indexed using an `obd_minor` number (see Source Code 8). An obd device can be identified using its minor number, name or uuid. A uuid is a unique identifier that Lustre assigns for obd devices. `lctl dl` utility (described in Chapter 3. Section 3.2.3) can be used to view all local obd devices and their uuids on Lustre clients and Lustre servers.

Source Code 6. obd_devs array defined in obdclass/genops.c

```
static struct obd_device *obd_devs[MAX_OBD_DEVICES];
```

Source Code 7. MAX_OBD_DEVICES defined in include/obd.h

```
#define MAX_OBD_DEVICES 8192
```

5.2 obd_device Structure

The structure that defines an obd device is shown in Source Code 8.

Source Code 8. obd_device structure defined in include/obd.h

```
struct obd_device {
        struct obd_type                 *obd_type;
        __u32                            obd_magic;
        int                              obd_minor;
        struct lu_device                *obd_lu_dev;
        struct obd_uuid                  obd_uuid;
        char                             obd_name[MAX_OBD_NAME];
        unsigned long
                obd_attached:1,
                obd_set_up:1,
                . . . . .
                obd_stopping:1,
                obd_starting:1,
                obd_force:1,
                . . . . .
        struct rhashtable               obd_uuid_hash;
        struct rhltable                 obd_nid_hash;
        struct list_head        obd_nid_stats;
        struct list_head        obd_exports;
        struct list_head        obd_unlinked_exports;
        struct list_head        obd_delayed_exports;
        struct obd_export       *obd_self_export;
        struct obd_export       *obd_lwp_export;
        struct kset                     obd_kset;
        struct kobj_type                obd_ktype;
        . . . . .

};
```

The first field in this structure is `obd_type` (shown in Source Code 11) that defines the type of the obd device - a metadata or bulk data device or both. `obd_magic` is used to identify data corruption with an obd device. Lustre assigns a magic number to the obd device during its creation phase and later asserts it in different parts of the source code to make sure that it returns the same magic number to ensure data integrity. As described in previous Section `obd_minor` is the index of the obd device in `obd_devs` array. An `lu_device` entry indicates if the obd device is a real device such as an `ldiskfs` or `zfs` based block device. `obd_uuid` and `obd_name` fields are used for uuid and name of the obd device as the field names suggest. `obd_device` structure also includes various flags to indicate the current status of the obd device. Some of those are `obd_attached` (completed attach), `obd_set_up` (finished setup), `abort_recovery` (recovery expired), `obd_stopping` (started cleanup), `obd_starting` (started setup) and so on. `obd_uuid_hash` and `obd_nid_hash` are `uuid-export` and `nid-export` hash tables for the obd device respectively. An obd device is also associated with several linked lists pointing to `obd_nid_stats`, obd_exports, obd_unlinked_exports and obd_delayed_exports. Some of the remaining relevant fields of this structure are obd_exports, kset and kobject device model abstractions, timeouts for recovery, proc entries, directory entry, procfs and debugfs variables.

5.3 MGC Life Cycle

As described in Chapter 4. MGC is the first obd device setup and started by Lustre in the obd device life cycle. To understand the lifecycle of MGC obd device let us start from the generic file system mount function vfs_mount(). vfs_mount() is directly invoked by the mount system call from the user and handles the generic portion of mounting a file system. It then invokes file system specific mount function, that is lustre_mount() in case of Lustre. The lustre_mount() defined in llite/llite_lib.c invokes the kernel function mount_nodev() (as shown in Source Code 9) which invokes lustre_fill_super() as its call back function.

Source Code 9. lustre_mount() function defined in llite/llite_lib.c

```
static struct dentry *lustre_mount(struct file_system_type *fs_type, int flags,
                                   const char *devname, void *data)
{
        return mount_nodev(fs_type, flags, data, lustre_fill_super);
}
```

lustre_fill_super() function is the entry point for the mount call into Lustre. This function initializes lustre superblock, which is used by the MGC to write a local copy of config log. The lustre_fill_super() routine calls ll_fill_super() which initializes a config log instance specific for the superblock. The config_llog_instance structure is defined in include/obd_class.h as shown in Source Code 10. The cfg_instance field in this structure is unique to this superblock. This unique cfg_instance is obtained using ll_get_cfg_instance() function defined in include/obd_class.h. The config_llog_instance structure also has a uuid (obtained from obd_uuid field of ll_sb_info structure defined in llite/llite_internal.h) and a callback handler defined by the function class_config_llog_handler(). We will come back to this callback handler later in the MGC life cycle process. The color coded blocks in Figure 11 were also part of mgc_setup() call graph shown in Figure 8 in Chapter 4..

Source Code 10. config_llog_instance structure is defined in include/obd_class.h

```
struct config_llog_instance {
        unsigned long            cfg_instance;
        struct super_block      *cfg_sb;
        struct obd_uuid          cfg_uuid;
        llog_cb_t                cfg_callback;
        int                      cfg_last_idx; /* for partial llog processing */
        int                      cfg_flags;
        __u32                    cfg_lwp_idx;
        __u32                    cfg_sub_clds;
};
```

The file system name field (ll_fsinfo) of ll_sb_info structure is populated by copying the profile name obtained using the get_profile_name() function. get_profile_name() defined in `include/lustre_disk.h` obtains a profile name corresponding to the mount command issued from the user from the `lustre_mount_data` structure.

Then `ll_fill_super()` then invokes the `lustre_process_log()` function (see Figure 11) which gets the config logs from MGS and starts processing them. This function is called from both Lustre clients and Lustre servers and it will continue to process new statements appended to the logs. `lustre_process_log()` is defined in `obdclass/obd_mount.c`. The three parameters passed to this function are superblock, logname and config log instance. The config instance is unique to the super block which is used by the MGC to write to the local copy of the config log and the logname is the name of the llog to be replicated from the MGS. The config log instance is used to keep the state for the specific config log (can be from ost1, ost2, Lustre client etc.) and is added to the MGC's list of logs to follow. `lustre_process_log()` then calls `obd_process_config()` that uses the `OBP` macro (refer Section 4.3) to call MGC specific `mgc_process_config()` function. `mgc_process_config()` gets the config log from the MGS and processes it to start any services. Logs are also added to the list of logs to watch.

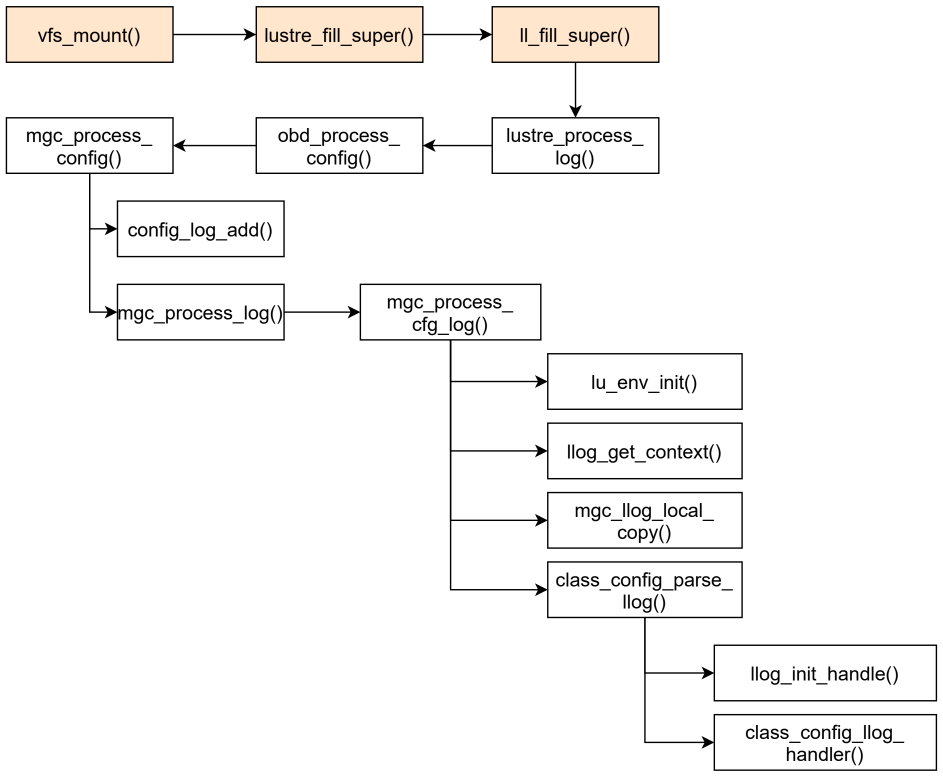


Figure 11. Obd device life cycle workflow for MGC

We now describe the detailed workflow of `mgc_process_config()` by describing the functionalities of each sub-function that it invokes. The `config_log_add()` function categorizes the data in config log based on if the data is related to - ptl-rpc layer, configuration parameters, nodemaps and barriers. The log data related to each of these categories is then copied to memory using the function `config_log_find_or_add()`. `mgc_process_config()` next calls `mgc_process_log()` and it gets a config log from MGS and processes it. This function is called for both Lustre clients and Lustre servers to process the configuration log from the MGS. The MGC enqueues a DLM lock on the log from the MGS and if the lock gets revoked, MGC will be notified by the lock cancellation callback that the config log has changed, and will enqueue another MGS lock on it, and then continue processing the new additions to the end of the log. Lustre prevents the updation of the same log by multiple processes at the same time. The `mgc_process_log()` then calls `mgc_process_cfg_log()` function which reads the log and creates a local copy of the log on the Lustre client or Lustre server. This function first initializes an environment and a context using `lu_env_init()` and `llog_get_context()` respectively. The `mgc_llog_local_copy()` routine is used to create a local copy of the log with the environment and context previously initialized. Real time changes in the log are parsed using the function `class_config_parse_llog()`. Under read only mode, there will be no local copy or local copy will be incomplete, so Lustre will try to use remote llog first.

The `class_config_parse_llog()` function is defined in `obdclass/obd_config.c`. The arguments passed to this function are the environment, context and config log instance initialized in `mgc_process_cfg_log()` function and the config log name. The first log that is being parsed by the `class_config_parse_llog()` function is `start_log`. `start_log` contains configuration information for various Lustre file system components, obd devices and file system mounting process. `class_config_parse_llog()` first acquires a lock on the log to be parsed using a handler function (`llog_init_handle()`). It then continues the processing of the log from where it last stopped till the end of the log. To process the logs two entities are used by this function - 1) an index to parse through the data in the log, and 2) a callback function that processes and interprets the data. The call back function can be a generic handler function like `class_config_llog_handler()` or it can be customized. Note that this is the call back handler initialized by the `config_llog_instance` structure as previously mentioned (see Source Code 10). Additionally, the callback function provides a config marker functionality that allows to inject special flags for selective processing of data in the log. The callback handler also initializes `lustre_cfg_bufs` to temporarily store the log data. Afterwards the following actions take place in this function: translate log names to obd device names, append uuid with obd device name for each Lustre client mount and finally attach the obd device.

Each obd device then sets up a key to communicate with other devices through secure ptl-rpc layer. The rules for creating this key are stored in the config log. The obd device then creates a connection for communication. Note that the start log contains all state information for all configuration devices and the lustre configuration buffer (`lustre_cfg_bufs`) stores this information temporarily. The obd device then use this buffer to consume log data. The start log resembles to a virtual log file and it is never stored on the disk. After creating a connection, the handler performs data mining on the logs to extract information (uuid, nid etc.) required to form Lustre `config_logs`. The parameter `llog_rec_hdr` (passed with `class_config_llog_handler()` function) decides what type of information should be parsed from the logs. For instance `OBD_CFG_REC` indicates the handler to scan obd device configuration information and `CHANGELOG_REC` asks to parse for changelog records. Using the extracted nid and uuid information about the obd device, the handler now invokes `class_process_config()` routine. This function repeats the cycle of obd device creation for other obd devices. Notice that the only obd device exists in Lustre at this point in the life cycle is MGC. The `class_process_config()` function calls the generic obd class functions such as `class_attach()`, `class_add_uuid()`, `class_setup()` depending upon the `lcfg_command` that it receives for a specific obd device.

5.4 Obd Device Life Cycle

In this Section we describe the work flow of various obd device life cycle functions such as `class_attach()`, `class_setup()`, `class_precleanup()`, `class_cleanup()`, and `class_detach()`.

5.4.1 class_attach()

The first method that is called in the life cycle of an obd device is `class_attach()` and the corresponding lustre config command is `LCFG_ATTACH`. The `class_attach()` method is defined in `obdclass/obd_config.c`. It registers and adds the obd device to the list of obd devices. The list of obd devices is defined in `obdclass/genops.c` using `*obd_devs[MAX_OBD_DEVICES]`. The attach function first checks if the obd device type being passed is valid. The `obd_type` structure is defined in `include/obd.h` (as shown in Source code 11). Two types of operations defined in this structure are `obd_ops` (i.e., data operations) and `md_ops` (i.e., metadata operations). These operations determine if the obd device is destined to perform data or metadata operations or both.

The `lu_device_type` field of `obd_type` structure makes sense only for real block devices such as `zfs` and `ldiskfs` osd devices. Furthermore the `lu_device_type` differentiates metadata and data devices using the tags `LU_DEVICE_MD` and `LU_DEVICE_DT` respectively. An example of an `lu_device_type` structure defined for `ldiskfs osd_device_type` is shown in Source Code 12.

Source Code 11. obd_type structure defined in include/obd.h

```
struct obd_type {
        const struct obd_ops    *typ_dt_ops;
        const struct md_ops     *typ_md_ops;
        struct proc_dir_entry   *typ_procroot;
        struct dentry           *typ_debugfs_entry;
#ifdef HAVE_SERVER_SUPPORT
        bool                     typ_sym_filter;
#endif
        atomic_t                 typ_refcnt;
        struct lu_device_type   *typ_lu;
        struct kobject           typ_kobj;
};
```

Source Code 12. lu_device_type structure for ldiskfs osd_device_type defined in osd-ldiskfs/osd_handler.c

```
static struct lu_device_type osd_device_type = {
        .ldt_tags     = LU_DEVICE_DT,
        .ldt_name     = LUSTRE_OSD_LDISKFS_NAME,
        .ldt_ops      = &osd_device_type_ops,
        .ldt_ctx_tags = LCT_LOCAL,
};
```

The `class_attach()` then calls a `class_newdev()` function which creates, allocates a new obd device and initializes it. A complete workflow of the `class_attach()` function is shown in Figure 12. The `class_get_type()` function invoked by `class_newdev()` registers already created obd device and loads the obd device module. All obd device loaded has metadata or data operations (or both) defined for them. For instance the LMV obd device has its `md_ops` and `obd_ops` defined in structures `lmv_md_ops` and `lmv_obd_ops` respectively. These structures and the associated operations can be seen in `lmv/lmv_obd.c` file. The `obd_minor` initialized here is the index of the obd device in `obd_devs` array.

The obd device then creates a self export using the function `class_new_export_self()`. The `class_new_export_self()` function invokes a `__class_new_export()` function which creates a new export, adds it to the hash table of exports and returns a pointer to it. Note that a self export is created only for a client obd device. The reference count for this export when created is 2, one for the hash table reference and the other for the pointer returned by this function itself. This function populates the `obd_export` structure defined in `include/lustre_export.h` (shown in Source Code 13). Various fields associated with this structure are explained in the next Section. Two functions that are used to increment and decrement the reference count for obd devices are `class_export_get()` and `class_export_put()` respectively. The last part of `class_attach()` is registering/listing the obd device in the `obd_devs` array which is done through `class_register_device()` function. This functions assigns a minor number to the obd device that can be used to lookup the device in the array.

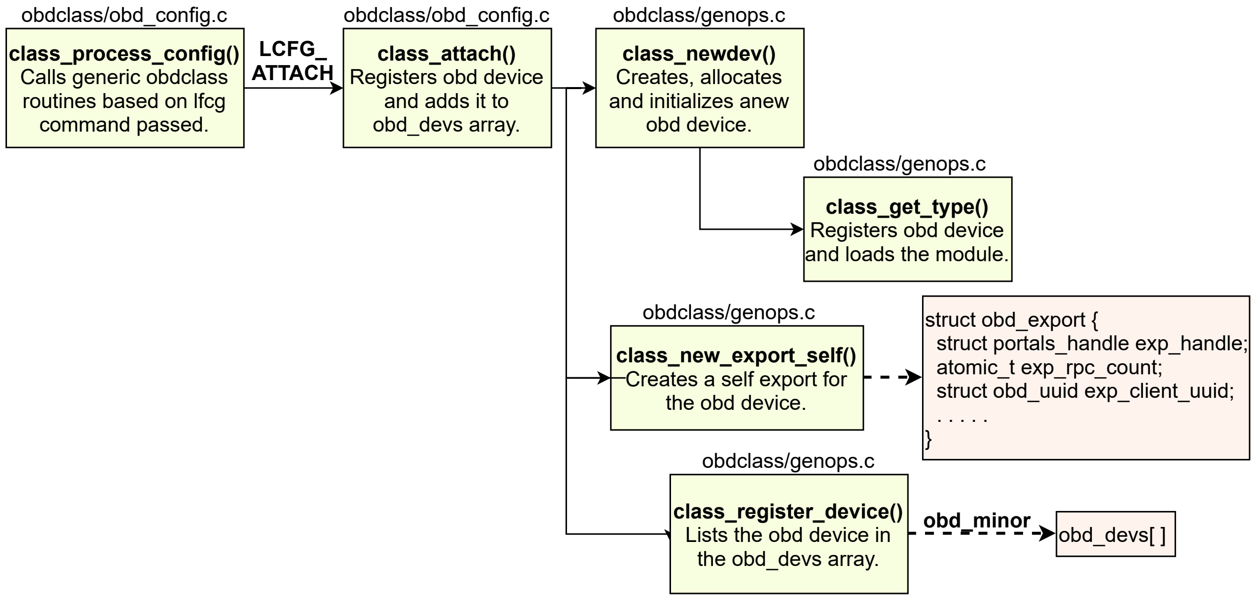

obdclass/obd_config.c
class_process_config()
Calls generic obdclass routines based on lfcg command passed.
LCFG_ ATTACH
obdclass/obd_config.c
class_attach()
Registers obd device and adds it to obd_devs array.
obdclass/genops.c
class_newdev()
Creates, allocates and initializes anew obd device.
obdclass/genops.c
class_get_type()
Registers obd device and loads the module.
obdclass/genops.c
class_new_export_self()
Creates a self export for the obd device.
struct obd_export {
struct portals_handle exp_handle;
atomic_t exp_rpc_count;
struct obd_uuid exp_client_uuid;
. . . . .
}
obdclass/genops.c
class_register_device()
Lists the obd device in the obd_devs array.
obd_minor
obd_devs[ ]

Figure 12. Workflow of class_attach() function in obd device lifecycle

5.4.2 obd_export Structure

This Section describes some of the relevant fields of the `obd_export` structure (shown in Source Code 13) that represents a target side export connection (using ptlrpc layer) for obd devices in Lustre. This is also used to connect between layers on the same node when there is no network connection between the nodes. For every connected client there exists an export structure on the server attached to the same obd device. Various fields of this structure are described below.

- `exp_handle` - On connection establishment, the export handle id is provided to client and the subsequent client RPCs contain this handle id to identify which export they are talking to.

- Set of counters described below is used to track where export references are kept. `exp_rpc_count` is the number of RPC references, `exp_cb_count` counts commit callback references, `exp_replay_count` is the number of queued replay requests to be processed and `exp_locks_count` keeps track of the number of lock references.

Source Code 13. obd_export structure defined in include/lustre_export.h

```
struct obd_export {
        struct portals_handle   exp_handle;
        atomic_t                exp_rpc_count;
        atomic_t                exp_cb_count;
        atomic_t                exp_replay_count;
        atomic_t                exp_locks_count;
#if LUSTRE_TRACKS_LOCK_EXP_REFS
        struct list_head        exp_locks_list;
        spinlock_t              exp_locks_list_guard;
#endif
        struct obd_uuid         exp_client_uuid;
        struct list_head        exp_obd_chain;
        struct work_struct      exp_zombie_work;
        struct list_head        exp_stale_list;
        struct rhash_head       exp_uuid_hash;
        struct rhlist_head      exp_nid_hash;
        struct hlist_node       exp_gen_hash;
        struct list_head        exp_obd_chain_timed;
        struct obd_device      *exp_obd;
        struct obd_import       *exp_imp_reverse;
        struct nid_stat         *exp_nid_stats;
        struct ptlrpc_connection *exp_connection;
        __u32                    exp_conn_cnt;
        struct cfs_hash         *exp_lock_hash;
        struct cfs_hash         *exp_flock_hash;
};
```

- `exp_locks_list` maintains a linked list of all the locks and `exp_locks_list_guard` is the spinlock that protects this list.
- `exp_client_uuid` is the UUID of client connected to this export.
- `exp_obd_chain` links all the exports on an obd device.
- `exp_zombie_work` is used when the export connection is destroyed.
- The structure also maintains several hash tables to keep track of `uuid-exports`, `nid-exports` and last received messages in case of recovery from failure. (`exp_uuid_hash, exp_nid_hash and exp_gen_hash`).
- The obd device for this export is defined by the pointer `*exp_obd`.

- `*exp_connection` - This defines the portal rpc connection for this export.
- `*exp_lock_hash` - This lists all the ldlm locks granted on this export.
- This structure also has additional fields such as hashes for posix deadlock detection, time for last request received, linked list to replay all requests waiting to be replayed on recovery, lists for RPCs handled, blocking ldlm locks and special union to deal with target specific data.

5.4.3 class_setup()

The primary duties of `class_setup()` routine are create hashtables and self-export, and invoke the obd type specific setup() function. As an initial step this function obtains the obd device from `obd_devs` array using `obd_minor` number and asserts the `obd_magic` number to make sure data integrity. Then it sets the `obd_starting` flag to indicate that the set up of this obd device has started (refer Source Code 8). Next the `uuid-export` and `nid-export` hashtables are setup using Linux kernel builtin functions `rhashtable_init()` and `rhltable_init()`. For the `nid-stats` hashtable Lustre uses its custom implementation of hashtable namely `cfs_hash`.

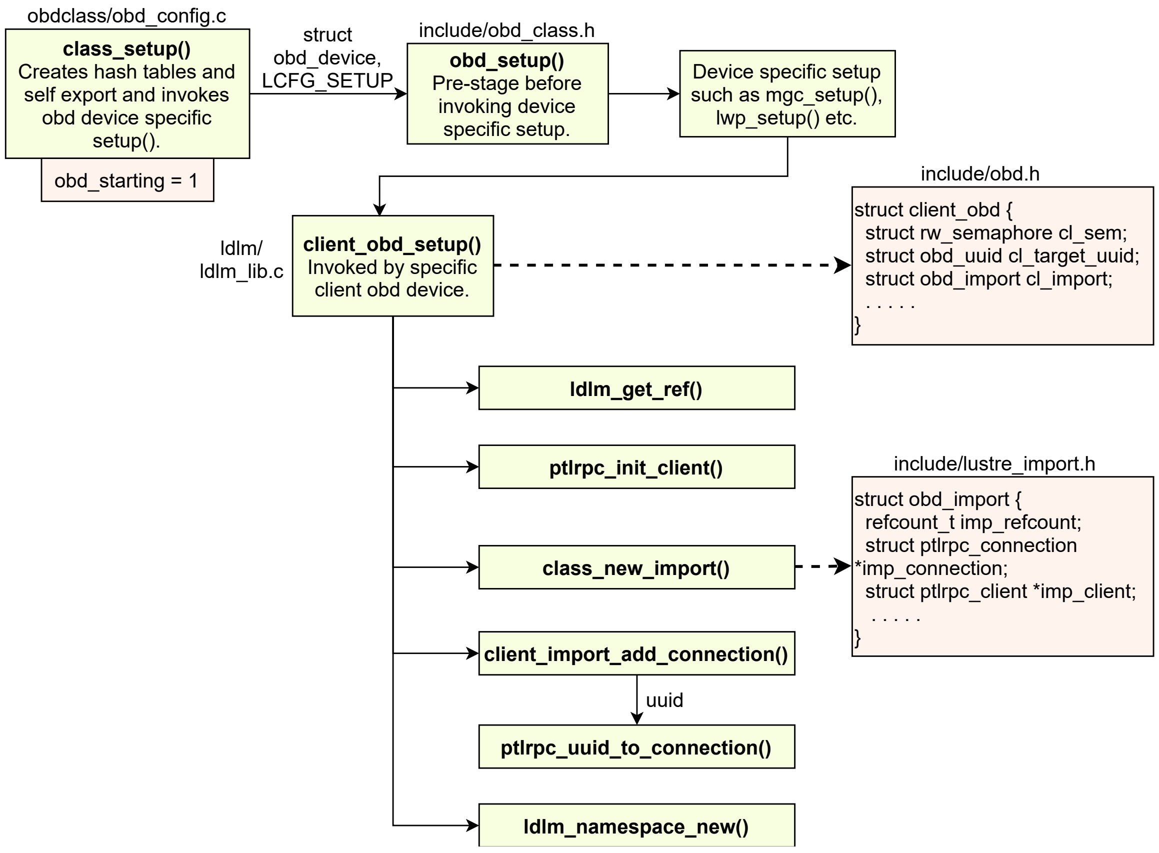

obdclass/obd_config.c
class_setup()
Creates hash tables and self export and invokes obd device specific setup().
obd_starting = 1
struct obd_device, LCFG_SETUP
include/obd_class.h
obd_setup()
Pre-stage before invoking device specific setup.
Device specific setup such as mgc_setup(), lwp_setup() etc.
ldlm/ldlm_lib.c
client_obd_setup()
Invoked by specific client obd device.
include/obd.h
struct client_obd {
struct rw_semaphore cl_sem;
struct obd_uuid cl_target_uuid;
struct obd_import cl_import;
. . . . .
}
ldlm_get_ref()
ptlrpc_init_client()
class_new_import()
include/lustre_import.h
struct obd_import {
refcount_t imp_refcount;
struct ptlrpc_connection *imp_connection;
struct ptlrpc_client *imp_client;
. . . . .
}
client_import_add_connection()
uuid
ptlrpc_uuid_to_connection()
ldlm_namespace_new()

Figure 13. Workflow of class_setup() function in obd device lifecycle

A generic device setup function `obd_setup()` defined in `include/obd_class.h` is then invoked by class_setup() by passing the odb_device structure populated and the corresponding lcfg command (LCFG_SETUP). This leads to the invocation of device specific setup routines from various subsystems such as mgc_setup(), lwp_setup(), osc_setup_common() and so on. All of these setup routines invoke a client_obd_setup() routine that acts as a pre-setup stage before the creation of imports for the clients as shown in Figure 13. The client_obd_setup() (see ldlm/ldlm_lib.c) function populates client_obd structure defined in include/obd.h (shown in Source Code 14). Note that the client_obd_setup() routine is called only in case of client obd devices like osp, lwp, mgc, osc, and mdc.

Source Code 14. client_obd structure defined in include/obd.h

```
struct client_obd {
        struct rw_semaphore      cl_sem;
        struct obd_uuid          cl_target_uuid;
        struct obd_import       *cl_import; /* ptlrpc connection state */
        size_t                   cl_conn_count;
        __u32               cl_default_mds_easize;
        __u32               cl_max_mds_easize;
        struct cl_client_cache  *cl_cache;
        atomic_long_t           *cl_lru_left;
        atomic_long_t            cl_lru_busy;
        atomic_long_t            cl_lru_in_list;
        . . . . .
};
```

client_obd structure is mainly used for page cache and extended attributes management. It comprises of fields pointing to obd device uuid and import interfaces, counter to keep track of client connections and fields to represent maximum and default extended attribute sizes. Few other fields used for cache handling are cl_cache (LRU cache for caching OSC pages), cl_lru_left (available LRU slots per OSC cache), cl_lru_busy (number of busy LRU pages), and cl_lru_in_list (number of LRU pages in the cache for this client_obd). Please also refer source code to see additional fields in the structure.

The client_obd_setup() then obtains an LDLM lock to setup the LDLM layer references for this client obd device. Further it sets up ptl-rpc request and reply portals using the ptlrpc_init_client() routine defined in ptlrpc/client.c. The client_obd structure defines a pointer to the obd_import structure defined in include/lustre_import.h. The obd_import structure represents ptl-rpc imports that are client-side view of remote targets. A new import connection for the obd device is created using the function class_new_import(). The class_new_import() method populates obd_import structure defined in include/lustre_import.h (see Source Code 15).

The obd_import structure represents the client side view of a remote target. This structure mainly consists of fields representing ptl-rpc layer client and active connections on it, client side ldlm handle and various flags representing the status of imports such as imp_invalid, imp_deactive, and imp_replayable. There are also linked lists pointing to lists of requests that are retained for replay, waiting for a reply, and waiting for recovery to complete.

The client_obd_setup() then adds an initial connection for the obd device to the ptl-rpc layer by invoking client_import_add_conn() method. This method uses ptl-rpc layer specific routine ptlrpc_uuid_to_connection() to return a ptl-rpc connection specific for the uuid passed for the remote obd device. Finally `client_obd_setup()` creates a new ldlm namespace for the obd device that it just set up using the `ldlm_namespace_new()` routine. This completes the setup phase in the obd device lifecycle and the newly setup obd device can now be used for communications between subsystems in Lustre.

Source Code 15. obd_import structure defined in include/lustre_import.h

```
struct obd_import {
        refcount_t                imp_refcount;
        struct lustre_handle      imp_dlm_handle;
        struct ptlrpc_connection *imp_connection;
        struct ptlrpc_client     *imp_client;
        struct list_head        imp_replay_list;
        struct list_head        imp_sending_list;
        struct list_head        imp_delayed_list;
        enum lustre_imp_state     imp_state;
        struct obd_import_conn   *imp_conn_current;
        unsigned long             imp_invalid:1,
                                  imp_deactive:1,
                                 imp_replayable:1,
        . . . . .
};
```

5.4.4 class_precleanup() and class_cleanup()

Lustre unmount process begins from the `ll_umount_begin()` function defined as part of the `lustre_super_operations` structure (shown in Source Code 16). The `ll_umount_begin()` function accepts a `super_block` from which the metadata and data exports for the `obd_device` are extracted using the `class_exp2obd()` routine. The `obd_force` flag from `obd_device` structure is set to indicate that cleanup will be performed even though the obd reference count is greater than zero. Then it periodically checks and waits to finish until there are no outstanding requests from vfs layer.

Source Code 16. lustre_super_operations structure defined in llite/super25.c

```
const struct super_operations lustre_super_operations =
{
        .alloc_inode   = ll_alloc_inode,
        .destroy_inode = ll_destroy_inode,
        .drop_inode    = ll_drop_inode,
        .evict_inode   = ll_delete_inode,
        .put_super     = ll_put_super,
        .statfs        = ll_statfs,
        .umount_begin  = ll_umount_begin,
        .remount_fs    = ll_remount_fs,
        .show_options  = ll_show_options,
};
```

The cleanup cycle then invokes the `ll_put_super()` routine defined in `llite/llite_lib.c`. This

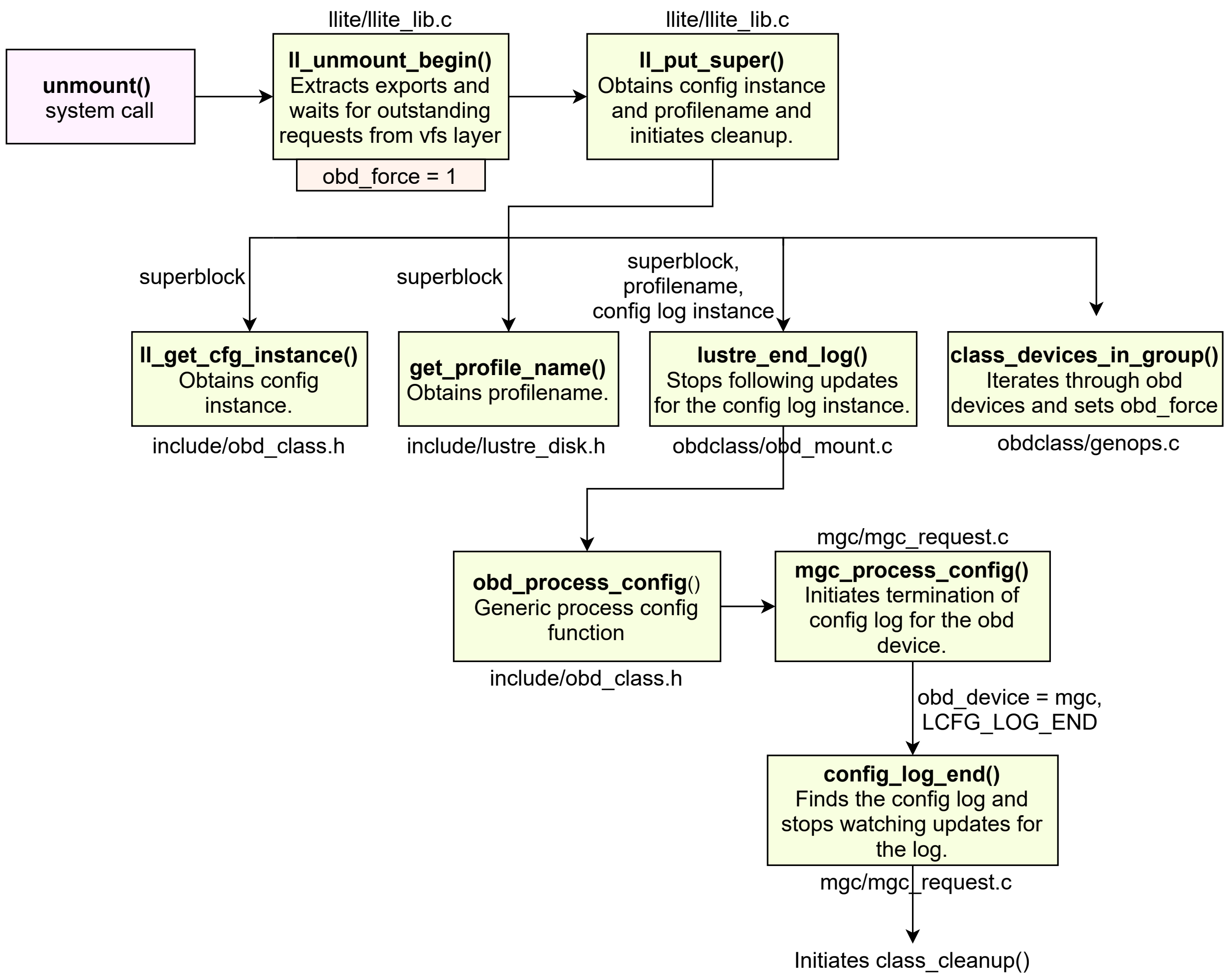

llite/llite_lib.c
llite/llite_lib.c
unmount() system call
ll_unmount_begin() Extracts exports and waits for outstanding requests from vfs layer
obd_force = 1
ll_put_super() Obtains config instance and profilename and initiates cleanup.
superblock
superblock
superblock, profilename, config log instance
ll_get_cfg_instance() Obtains config instance.
get_profile_name() Obtains profilename.
lustre_end_log() Stops following updates for the config log instance.
class_devices_in_group() Iterates through obd devices and sets obd_force
include/obd_class.h
include/lustre_disk.h
obdclass/obd_mount.c
obdclass/genops.c
mgc/mgc_request.c
obd_process_config() Generic process config function
mgc_process_config() Initiates termination of config log for the obd device.
include/obd_class.h
obd_device = mgc, LCFG_LOG_END
config_log_end() Finds the config log and stops watching updates for the log.
mgc/mgc_request.c
Initiates class_cleanup()

Figure 14. Lustre unmounting and initiation of class_cleanup() in obd device lifecycle.

function obtains the `cfg_instance` and profile name corresponding to the `super_block` using `ll_get_cfg_instance()` and `get_profile_name()` functions respectively. Next it invokes `lustre_end_log()` routine by passing the super block, profile name and a config llog instance initialized here. The `lustre_end_log()` function defined in `obdclass/obd_mount.c` ensures to stop following updates for the config log corresponding to the config llog instance passed. `lustre_end_log()` resets lustre config buffers and calls `obd_process_config()` by passing the lcfg command `LCFG_LOG_END` and MGC as obd device. This results in the invocation of `mgc_process_config()` which calls `config_log_end()` method when `LCFG_LOG_END` is passed. The `config_log_end()` finds the config log and stops watching updates for the log.

Further `ll_put_super()` invokes `class_devices_in_group()` method which iterates through the obd devices with same group uuid and sets the `obd_force` flag for all the devices. Afterwards it calls `class_manual_cleanup()` routine which invokes obdclass functions `class_cleanup()` and `class_detach()` in the order. The `class_cleanup()` is invoked through `class_process_config()` by passing the `LCFG_CLEANUP` command.

`class_cleanup()` starts the shut down process of the obd device. This first sets the `obd_stopping` flag to indicate that cleanup has started and then waits for any already arrived connection requests to complete. Once all the requests are completed it disconnects all the exports using `class_disconnect_exports()` function (shown in Figure 14). It then invokes obd generic function `obd_precleanup()` that ensures that all exports get destroyed. `obd_precleanup()` calls device specific precleanup function (e.g. `mgc_precleanup()`). `class_cleanup()` then destroys the `uuid-export`, `nid-export`, and `nid-stats` hashtables and invokes `class_decref()` function. `class_decref()` function asserts that all exports are destroyed.

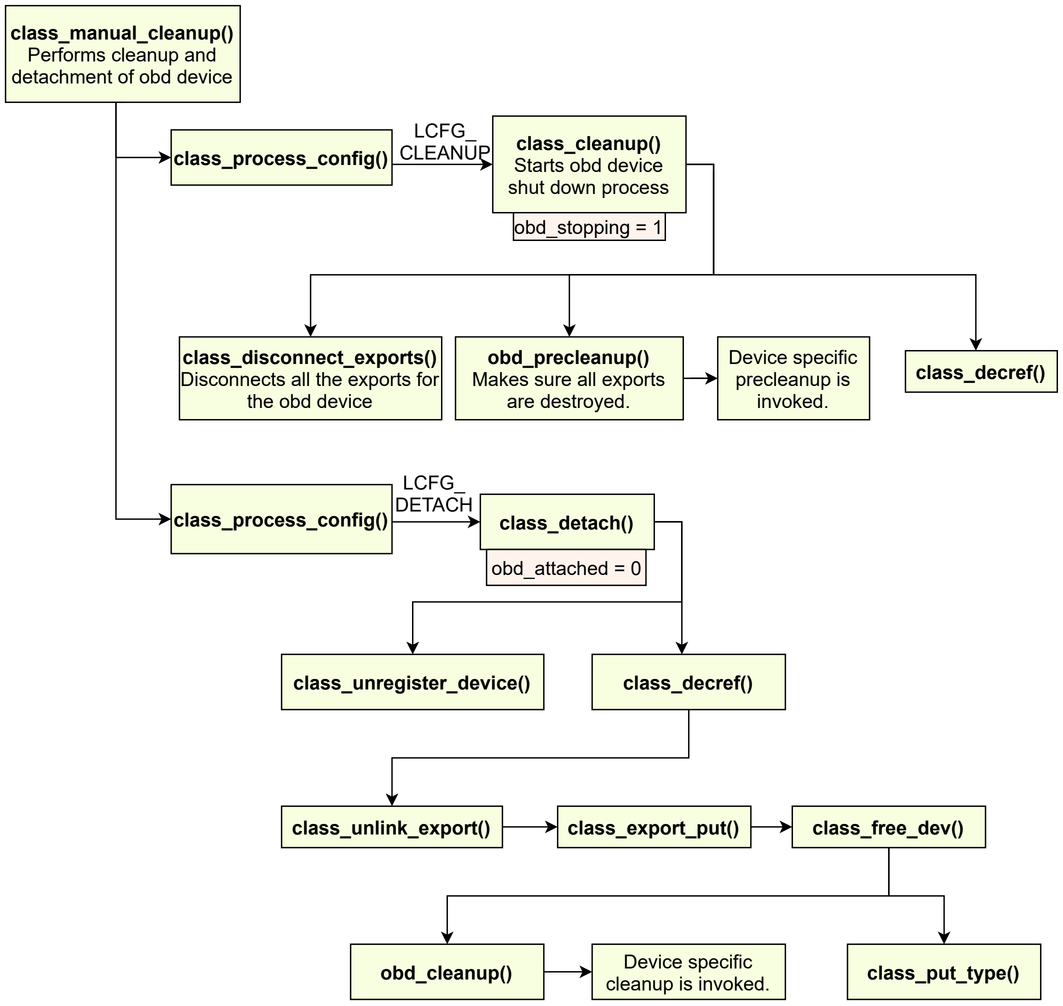

class_manual_cleanup()
Performs cleanup and detachment of obd device
class_process_config()
LCFG_ CLEANUP
class_cleanup()
Starts obd device shut down process
obd_stopping = 1
class_disconnect_exports()
Disconnects all the exports for the obd device
obd_precleanup()
Makes sure all exports are destroyed.
Device specific precleanup is invoked.
class_decref()
class_process_config()
LCFG_ DETACH
class_detach()
obd_attached = 0
class_unregister_device()
class_decref()
class_unlink_export()
class_export_put()
class_free_dev()
obd_cleanup()
Device specific cleanup is invoked.
class_put_type()

Figure 15. class_cleanup() workflow in obd device lifecycle.

`class_manual_cleanup()` then invokes `class_detach()` function by passing the `LCFG_DETACH` command. `class_detach()` (defined in `obdclass/obd_config.c`) makes the `obd_attached` flag to zero and unregisters the device (frees the slot in `obd_devs` array) using `class_unregister_device()` function. Next it invokes the `class_decref()` routine that destroys the last export (self export) by calling `class_unlink_export()` method. `class_unlink_export()` calls `class_export_put()` that frees the obd device using `class_free_dev()` function. `class_free_dev()` calls device specific cleanup through `obd_cleanup()` and finally invokes `class_put_type()` routine that unloads the module. This is the end of the life cycle for the obd device. An end to end workflow of `class_cleanup()` routine is illustrated in Figure 15.

5.5 Imports and Exports

Obd devices in Lustre are components including lmv, lod, lov, mdc, mdd, mdt, mds, mgc, mgs, obdecho, ofd, osc, osd-ldsikfs, osd-zfs, osp, lwp, ost, and qmt. Among these mdc, mgc, osc, osp, and lwp are client obd devices meaning two server odb device components such as mdt and ost need one client device to establish communication between them. This is also applicable in case of a Lustre client communicating with Lustre servers. Client side obd devices consist of self export and import whereas server side obd devices consist of exports and reverse imports. A client obd device sends requests to the server using its import and the server receives requests using its export as illustrated in Figure 16. The imports on server obd devices are called reverse imports because they are used to send requests to the client obd devices. These requests are mostly callback requests sent by the server to clients infrequently. And the client uses it's self export to receive these callback requests from the server.

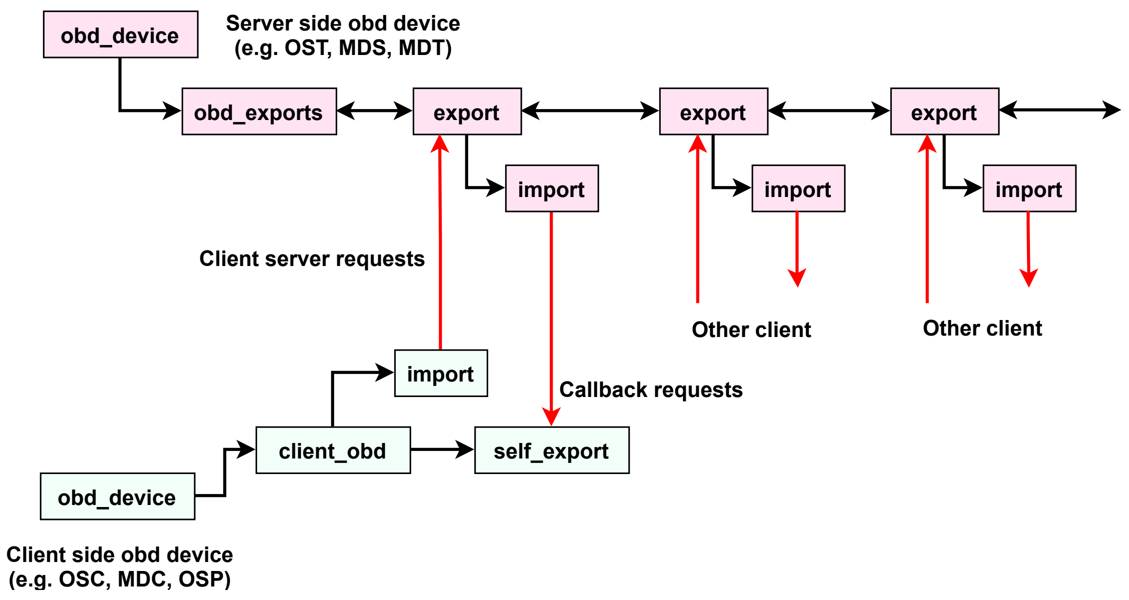


Figure 16. Import and export pair in Lustre

For any two obd devices to communicate with each other, they need an import and export pair [3]. For instance, let us consider the case of communication between ost and mdt obd devices. Logging into an OSS node and doing `lctl dl` shows the obd devices on the node and associated details (obd device status, type, name, uuid etc.). Examining `/sys/fs/lustre` directory can also show the obd devices corresponding to various device types. An example of the name of an obd device created for the data exchange between OST5 and MDT2 will be `MDT2-lwp-OST5`. This means that the client obd device that enables the communication here is lwp. A conceptual view of the communication between ost and mdt through import and export connections is shown in Figure 17. LWP (Light Weight Proxy) obd device manages connections established from ost to mdt, and mdts to mdt0. An lwp device is used in Lustre to send quota and FLD query requests (see Chapter 7.). Figure 17 also shows the communication between mdt and ost through osp client obd device.

The obdfilter directory from `/proc/fs/lustre` lists osts present on the OSS node. All of these osts have their export connections listed in the nid format in their respective `exports` directory. The export connection information is stored in a file called `export` in each of the export connections directory. Viewing the `export` file corresponding to MDT2 shows the following fields.

- `name`: Shows the name of the ost device.
- `client`: The nid of the client export connection. (nid of MDT2 in this example.)
- `connect_flags`: Flags representing various configurations for the lnet and ptl-rpc connections between the obd devices.
- `connect_data`: Includes fields such as `flags, instance, target_version, mdt_index and target_index`.
- `export_flags`: Configuration flags for export connection.
- `grant`: Represents target specific export data.

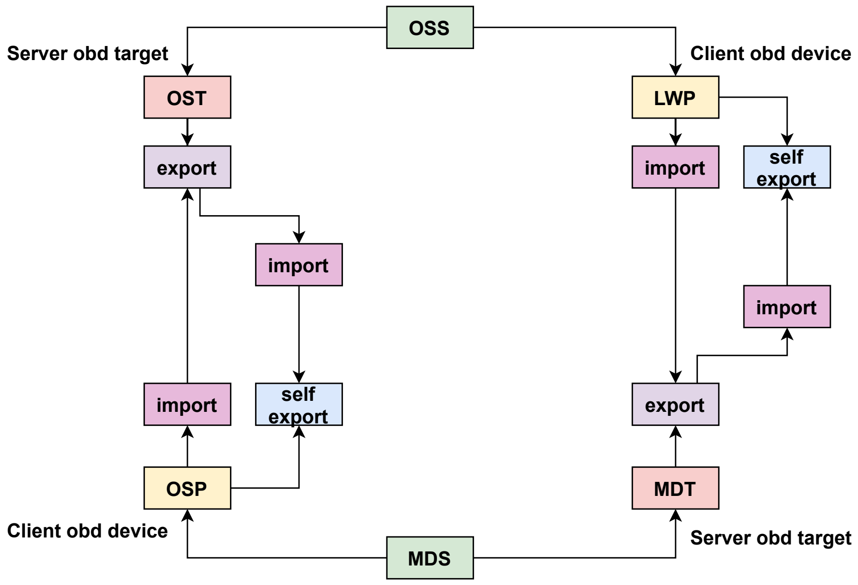


Figure 17. Communication between ost and mdt server obd devices in Lustre

5.6 Useful APIs in Obdclass

All obdclass related function declarations are listed in the file `include/obd_class.h` and their definitions can be seen in `obdclass/genops.c` Here we list some of the important obdclass function prototypes and their purpose for quick reference.

- `class_newdev()` - Creates a new obd device, allocates and initializes it.
- `class_free_dev()` - Frees an obd device.
- `class_unregister_device()` - Unregisters an obd device by feeing its slot in `obd_devs` array.
- `class_register_device()` - Registers obd device by finding a free slot in in `obd_devs` array and filling it with the new obd device.
- `class_name2dev()` - Returns minor number corresponding to an obd device name.
- `class_name2obd()` - Returns pointer to an `obd_device` structure corresponding to the device name.
- `class_uuid2dev()` - Returns minor number of an obd device when uuid is provided.
- `class_uuid2obd()` - Returns obd_device structure pointer corresponding to a uuid.
- `class_num2obd()` - Returns `obd_device` structure corresponding to a minor number.
- `class_dev_by_str()` - Finds an obd device in the `obd_devs` array by name or uuid. Also increments obd reference count if its found.
- `get_devices_count()` - Gets the count of the obd devices in any state.
- `class_find_client_obd()` - Searches for a client obd connected to a target obd device.
- `class_export_destroy()` - Destroys and export connection of an obd device.
- `__class_new_export()` - Creates a new export for an obd device and add its to the hash table of exports.

6. LIBCFS

6.1 Introduction

Libcfs provides APIs comprising of fundamental primitives for process management and debugging support in Lustre. Libcfs is used throughout LNet, Lustre, and associated utilities. Its APIs define a portable run time environment that is implemented consistently on all supported build targets [6]. Besides debugging support libcfs provides APIs for failure injection, Linux kernel compatibility, encryption for data, Linux 64 bit time addition, log collection using tracefile, string parsing support and capabilities for querying and manipulating CPU partition tables. Libcfs is the first module that Lustre loads. The module loading function can be found in `tests/test-framework.sh` script as shown in Source Code 17. When Lustre is mounted, `mount_facet()` function gets invoked and it calls `load_modules()` function. `load_modules()` invokes `load_modules_local()` that loads Lustre modules libcfs, lnet, obdclass, ptl-rpc, fld, fid, and lmv in the same order.

In the following Sections we describe libcfs APIs and functionalities in detail.

6.2 Data Encryption Support in Libcfs

Lustre implements two types of encryption capabilities - data on the wire and data at rest. Encryption over the wire protects data transfers between the physical nodes from Man-in-the-middle attacks. Whereas the objective of encrypting data at rest is protection against storage theft and network snooping. Lustre 2.14+ releases provides encryption for data at rest. Data is encrypted on Lustre client before being sent to servers and decrypted upon reception from the servers. That way applications running on Lustre client see clear text and servers see only encrypted text. Hence access to encryption keys is limited to Lustre clients.

Source Code 17. Libcfs module loading script (tests/test-framework.sh)

```
mount_facet() {
    . . . . .
    module_loaded lustre || load_modules
}

load_modules() {
    . . . . .
    load_modules_local
}

load_modules_local() {
    . . . . .
    load_module ../libcfs/libcfs/libcfs
    . . . . .
    load_module ../lnet/lnet/lnet
    . . . . .
    load_module obdclass/obdclass
    load_module ptlrpc/ptlrpc
    load_module ptlrpc/gss/ptlrpc_gss
    load_module fld/fld
    load_module fid/fid
    load_module lmv/lmv
    . . . . .
}
```

Data (at rest) encryption related algorithm and policy flags and data structures are defined in `libcfs/include/uapi/linux/llcrypt.h` (see Source Code 18 for encryption algorithm macros). Definition of an encryption key structure shown in Source Code 19 includes a name, the raw key and size fields. Maximum size of the encryption key is limited to `LLCRYPT_MAX_KEY_SIZE`. This file also contains ioctl definitions to add and remove encryption keys, and obtain encryption policy, and key status.

Source Code 18. Encryption algorithm macros defined in libcfs/include/uapi/linux/llcrypt.h

```
#define LLCRYPT_MODE_AES_256_XTS              1
#define LLCRYPT_MODE_AES_256_CTS              4
#define LLCRYPT_MODE_AES_128_CBC              5
#define LLCRYPT_MODE_AES_128_CTS              6
```

While userland headers for data encryption are listed in `libcfs/include/uapi/linux/llcrypt.h`, the corresponding kernel headers can be found in `libcfs/include/libcfs/crypto/llcrypt.h`. Some of the kernel APIs for data encryption are shown in Source code 20. The definitions of these APIs can be found in `libcfs/libcfs/crypto/hooks.c`.

Support functions for data encryption are defined in `libcfs/libcfs/crypto/crypto.c` file. These include:

- `llcrypt_release_ctx()` - Releases a decryption context.
- `llcrypt_get_ctx()` - Gets a decryption context.
- `llcrypt_free_bounce_page()` - Frees a ciphertext bounce page.
- `llcrypt_crypt_block()` - Encrypts or decrypts a single file system block of file contents.
- `llcrypt_encrypt_pagecache_blocks()` - Encrypts file system blocks from a page cache page.
- `llcrypt_encrypt_block_inplace()` - Encrypts a file system block in-place.
- `llcrypt_decrypt_pagecache_blocks()` - Decrypts file system blocks in a page cache page.
- `llcrypt_decrypt_block_inplace()` - Decrypts a file system block in-place.

Setup and cleanup functions (`llcrypt_init(), llcrypt_exit()`) for file system encryption are also defined here. `fname.c` implements functions to encrypt and decrypt filenames, allocate and free buffers for file name encryption and to convert a file name from disk space to user space. `keyring.c` and `keysetup.c` implement functions to manage cryptographic master keys and `policy.c` provides APIs to find supported policies, check the equivalency of two policies and policy context management.

Source Code 19. llcrypt_key structure defined in libcfs/include/uapi/linux/llcrypt.h

```
#define LLCRYPT_MAX_KEY_SIZE            64
struct llcrypt_key {
        __u32 mode;
        __u8 raw[LLCRYPT_MAX_KEY_SIZE];
        __u32 size;
};
```

APIs and data structures that provide support for data encryption over the wire are listed in `libcfs/include/libcfs/libcfs_crypto.h`. The data structures include definitions for hash algorithm type, name, size and key and enum for various hash algorithms such as `ALG_CRC32C, ALG_MD5, ALG_SHA1, ALG_SHA512` etc. Key APIs that help with data encryption are listed below.

- `cfs_crypto_hash_type()` - This function returns hash algorithm related information for the specified algorithm identifier. Hash information includes algorithm name, initial seed and hash size.
- `cfs_crypto_hash_name()` - This returns hash name for hash algorithm identifier.
- `cfs_crypto_hash_digestsize()` - Returns digest size for hash algorithm type.
- `cfs_crypto_hash_alg()` - Finds hash algorithm ID for the specified algorithm name.
- `cfs_crypto_crypt_type()` - Returns crypt algorithm information for the specified algorithm identifier.
- `cfs_crypto_crypt_name()` - Returns crypt name for crypt algorithm identifier.

- `cfs_crypto_crypt_keysize()` - Returns key size for crypto algorithm type.
- `cfs_crypto_crypt_alg()` - Finds crypto algorithm ID for the specified algorithm name.

Current version of Lustre supports only file name encryption whereas in future Lustre plans to extend the encryption capability for file contents as well.

6.3 CPU Partition Table Management

Libcfs includes APIs and data structures that help with CPU partition table management in Lustre. A CPU partition is a virtual processing unit and can have 1-N cores or 1-N NUMA nodes. Therefore a CPU partition is also viewed as a pool of processors.

Source Code 20. Kernel APIs for data encryption defined in libcfs/include/libcfs/crypto/llcrypt.h

```
//Prepares for a rename between possibly-encrypted directories
static inline int llcrypt_prepare_rename(struct inode *old_dir,
                                         struct dentry *old_dentry,
                                         struct inode *new_dir,
                                         struct dentry *new_dentry,
                                         unsigned int flags)
//Prepares to lookup a name in a possibly-encrypted directory
static inline int llcrypt_prepare_lookup(struct inode *dir,
                                         struct dentry *dentry,
                                         struct llcrypt_name *fname)

// Prepares to change a possibly-encrypted inode's attributes
static inline int llcrypt_prepare_setattr(struct dentry *dentry,
                                          struct iattr *attr)
//Prepares to create a possibly-encrypted symlink
static inline int llcrypt_prepare_symlink(struct inode *dir,
                                          const char *target,
                                          unsigned int len,
                                          unsigned int max_len,
                                          struct llcrypt_str *disk_link)
//Encrypts the symlink target if needed
static inline int llcrypt_encrypt_symlink(struct inode *inode,
                                          const char *target,
                                          unsigned int len,
                                          struct llcrypt_str *disk_link)
```

A CPU partition table (CPT) consists of a set of CPU partitions. CPTs can have two modes of operation, NUMA and SMP denoted by `CFS_CPU_MODE_NUMA` and `CFS_CPU_MODE_SMP` respectively. Users can specify total number of CPU partitions while creating a CPT and ID of a CPU partition always starts from 0. For example: if there are 8 cores in the system, creating a CPT:

```
with cpu_npartitions=4:
    core[0, 1] = partition[0], core[2, 3] = partition[1]
    core[4, 5] = partition[2], core[6, 7] = partition[3]
cpu_npartitions=1:
    core[0, 1, ... 7] = partition[0]
```

Users can also specify CPU partitions by a string pattern.

```
    cpu_partitions="0[0,1], 1[2,3]"
    cpu_partitions="N 0[0-3], 1[4-8]"
```

The first character “N” means following numbers are NUMA IDs. By default, Lustre modules should refer to the global `cfs_cpt_tab`, instead of accessing hardware CPUs directly, so concurrency of Lustre can be configured by `cpu_npartitions` of the global `cfs_cpt_tab`.

Source Code 21 and 22 show data structures that define CPU partition and CPT. A CPU partition consists of fields representing CPU mask (`cpt_cpumask`) and node mask (`*cpt_nodemask`) for the partition, NUMA distance between CPTs (`*cpt_distance`), spread rotor for NUMA allocator (`cpt_spread_rotor`) and NUMA node if `cpt_nodemask` is empty (`cpt_node`). Number of CPU partitions, structure representing partition tables and masks to represent all CPUs and nodes are the significant fields in the `cfs_cpt_table` structure.

Source Code 21. cfs_cpu_partition structure defined in libcfs/libcfs/libcfs_cpu.c

```
struct cfs_cpu_partition {
        cpumask_var_t                   cpt_cpumask;
        nodemask_t                      *cpt_nodemask;
        unsigned int                    *cpt_distance;
        unsigned int                    cpt_spread_rotor;
        int                             cpt_node;
};
```

Source Code 22. cfs_cpt_table structure defined in libcfs/libcfs/libcfs_cpu.c

```
struct cfs_cpt_table {
        unsigned int                    ctb_spread_rotor;
        unsigned int                    ctb_distance;
        int                             ctb_nparts;
        struct cfs_cpu_partition        *ctb_parts;
        int                             *ctb_cpu2cpt;
        cpumask_var_t                   ctb_cpumask;
        int                             *ctb_node2cpt;
        nodemask_t                      *ctb_nodemask;
};
```

Libcfs provides the following APIs to access and manipulate CPU partitions and CPTs.

- `cfs_cpt_table_alloc()` - Allocates a CPT given the number of CPU partitions.
- `cfs_cpt_table_free()` - Frees a CPT corresponding to the given reference.
- `cfs_cpt_table_print()` - Prints a CPT corresponding to the given reference.
- `cfs_cpt_number()` - Returns number of CPU partitions in a CPT.

- `cfs_cpt_online()` - returns the number of online CPTs.
- `cfs_cpt_distance_calculate()` - Calculates the maximum NUMA distance between all nodes in the from_mask and all nodes in the to_mask.

Additionally libcfs includes functions to initialize and remove CPUs, set and unset node masks and add and delete CPUs and nodes. Per CPU data and partition variables management functions are located in `libcfs/libcfs/libcfs_mem.c` file.

6.4 Debugging Support and Failure Injection

Lustre debugging infrastructure contains a number of macros that can be used to report errors and warnings. The debugging macros are defined in `libcfs/include/libcfs/libcfs_debug.h`. `CERROR, CNETERR, CWARN, CEMERG, LCONSOLE, CDEBUG` are examples of the debugging macros. Complete list of the debugging macros and their detailed description can be found in this link [2].

Failure macros defined in `libcfs_fail.h` are used to deliberately inject failure conditions in Lustre for testing purposes. `CFS_FAIL_ONCE, CFS_FAILv SKIP, CFS_FAULT, CFS_FAIL_SOME` are examples of such failure macros (see Source Code 23). Libcfs module defines the failure macros starting with the keyword `CFS` whereas Lustre redefines them in `lustre/include/obd_support.h` file starting with the keyword `OBD`. The hex values representing these failure macros are used in the `lctl set_param fail_loc` command inject specific failures. Instances of `OBD_FAIL` macro usage can be seen in `llite/vvp_io.c` file.

Source Code 23. CFS_FAIL macros defined in libcfs/include/libcfs/libcfs_fail.h

```
#define CFS_FAIL_SKIP        0x20000000 /* skip N times then fail */
#define CFS_FAIL_SOME        0x10000000 /* only fail N times */
#define CFS_FAIL_RAND        0x08000000 /* fail 1/N of the times */
#define CFS_FAIL_USR1        0x04000000 /* user flag */
```

6.5 Additional Supporting Software in Libcfs

Files located in `libcfs/include/libcfs/linux` furnish additional supporting software for Lustre for having 64-bit time, atomics, extended arrays and spin locks.

- `linux-time.h` - Implementation of portable time API for Linux for both kernel and user-level.
- `refcount.h` - Implements a variant of `atomic_t` specialized for reference counts.
- `xarray.h` - Implementation of large array of pointers that has the functionality of resizable arrays.
- `processor.h` - Provides `spin_begin()`, `spin_cpu_yield()` and `spin_until_cond()` capabilities for spin locks.

7. File Identifiers, FID Location Database, and Object Index

7.1 File Identifier (FID)

Lustre refers to all the data that it stores as objects. This includes not only the individual components of a striped file but also such things as directory entries, internal configuration files, etc. To identify an object, Lustre assigns a File IDentifier (FID) to the object that is unique across the file system. [‡] A FID is a 128-bit number that consists of three components: a 64-bit sequence number, a 32-bit object ID, and a 32-bit version number. The data structure for a FID is shown in Source Code 24. As noted in the code, the version number is not currently used but is reserved for future purposes.

Source Code 24. FID structure (include/uapi/linux/lustre/lustre_user.h)

```
struct lu_fid {
       /**
        * FID sequence. Sequence is a unit of migration: all files (objects)
        * with FIDs from a given sequence are stored on the same server.
        * Lustre should support 2^64 objects, so even if each sequence
        * has only a single object we can still enumerate 2^64 objects.
        **/
        __u64 f_seq;
        /* FID number within sequence. */
        __u32 f_oid;
        /**
         * FID version, used to distinguish different versions (in the sense
         * of snapshots, etc.) of the same file system object. Not currently
         * used.
         **/
        __u32 f_ver;
} __attribute__((packed));
```

Sequence numbers are controlled by the Lustre file system and allocated to clients. The entire space of sequence numbers is overseen by the sequence controller that runs on MDT0, and every storage target (MDTs and OSTs) runs a sequence manager. As the file system is started and the storage targets are brought online, each sequence manager contacts the sequence controller to obtain a unique range of sequence numbers (known as a super sequence). Every client that establishes a connection to a storage target will be granted a unique sequence number by the target's sequence manager. This ensures that no two clients share a sequence number and that the same sequence number will always map to the same storage target.

When a client creates a new object on a storage target, the client allocates a new FID to use for the object. The FID is created by using the sequence number granted to the client by the storage target and adding a unique object ID chosen by the client. The client maintains a counter for each sequence number and increments that counter when a new object ID is needed. This combination of target-specific sequence number and client-chosen object ID (along with a version number of zero) is used to populate the `lu_fid` structure for the new object. It should be noted that FIDs are never reused within the same Lustre file system (with a few exceptions for special internal-only objects). If a client exhausts a sequence number and cannot create more FIDs, the client will contact the target and request a new sequence number.

It is important to understand that the use of the term "client" in this context does not just refer to Lustre file system clients that present the POSIX file system interface to end-users. A FID client is any node that is responsible for creating new objects, and this can include other Lustre servers. When a Lustre file system

[‡]There is one exception to FID uniqueness. Certain internal files (like accounting logs) may use the same FID on multiple storage targets since that information is never directly accessed from outside of the target.

client uses the POSIX interface to create a new file, it will use a sequence number granted by an MDT target to construct a FID for the new file. This FID will be used to identify the object on the MDT that corresponds to this new file. However, the MDS server hosting the MDT will use the layout configuration for this new file to allocate objects on one or more OSTs that will contain the actual file data. In this scenario, the MDS is acting as a FID client to the OST targets. The MDS server will have been granted sequence numbers by the OST targets and use these sequence numbers to generate the FIDs that identify all the OST objects associated with the file layout.

7.1.1 Reserved Sequence Numbers and Object IDs

The sequence controller does not allocate certain sequence numbers to the sequence managers. These sequence numbers are reserved for special uses such as testing or compatibility with older Lustre versions. Information about these reserved sequence numbers can be found in `include/lustre_fid.h`. Below is a list of sequence ranges used by Lustre:

- IGIF (Inode and Generation In FID): sequence range = $[12, 2^{32} - 1]$
  This range is reserved for compatibility with older Lustre versions that previously identified MDT objects using the ext3 inode number on the backend file system. Since those inode values were only 32-bit integers, a FID can be generated for these older objects by simply using the inode number as the sequence number. Since ext3 reserves inodes 0-11 for internal purposed, these sequence numbers will be used for other internal purposes by Lustre.

- IDIF (object ID In FID): sequence range = $[2^{32}, 2^{33} - 1]$
  This range is reserved for older Lustre versions that identified OST objects using the inode number on the backend ext3 file system. Bit 33 is set to 1, and the OST index along with the high 16 bits of the inode number are encoded into the lower 32 bits of the sequence number.

- OST_MDT0: sequence = 0
  Used to identify existing objects on old formatted OSTs before the introduction of FID-on-OST.

- LLOG: sequence = 1
  Used internally for Lustre Log objects

- ECHO: sequence = 2
  Used for testing OST IO performance.

- OST_MDT1 ... OST_MAX: sequence range = [3-9]
  Used for testing file systems with multiple MDTs prior to the release of DNE.

- Normal Sequences: sequence range = $[2^{33}, 2^{64} - 1]$ This is the sequence range used in normal production and allocated to the sequence manager and clients. NOTE: The first 1024 sequence numbers in this range are reserved for system use.

The header file also contains some predefined object IDs that are used for local files such as user/group/project accounting logs, LFSCK checkpoints, etc. These are part of the `local_oid` enumeration, a portion of which is shown in Source Code 25.

Source Code 25. Portion of `local_oid` enumeration (include/lustre_fid.h)

```
enum local_oid {
        FLD_INDEX_OID           = 3UL,
        FID_SEQ_CTL_OID         = 4UL,
        FID_SEQ_SRV_OID         = 5UL,
        ...
        ACCT_USER_OID           = 15UL,
        ACCT_GROUP_OID          = 16UL,
        LFSCK_BOOKMARK_OID      = 17UL,
        ...
        LFSCK_NAMESPACE_OID     = 4122UL,
        REMOTE_PARENT_DIR_OID   = 4123UL,
        BATCHID_COMMITTED_OID   = 4125UL,
};
```

Unless otherwise noted, the remainder of this chapter will focus on FIDs that use Normal Sequences or ones reserved for special internal objects. It will not deal with sequences reserved for compatibility reasons (IGIF, IDIF, etc.).

7.1.2 fid Kernel Module

FID-related functions are built into the `fid` kernel module. The source code for this module is located in the `lustre/fid` directory. For Lustre clients, two files are used to build this module: `lproc_fid.c` and `fid_request.c`. The `lproc_fid.c` file just contains functions needed to support debugfs and won't be discussed in detail here.

The `fid_request.c` file contains the core functions needed to support the FID client functionality. The module entry/exit points are `fid_init()` and `fid_exit()`, but these functions just call `debugfs_create_dir(...)` and `debugfs_remove_recursive(...)` to add/remove the necessary debugfs entries. The real initialization starts in the `client_fid_init` function. This function is registered as part of the OBD operations (`struct obd_ops`) to be invoked by the MDC and OSP subsystems. The function's main responsibility is to allocate memory for a `lu_client_seq` structure which is then passed to `seq_client_init(..)` (an abbreviated version of which is shown in Source Code 26) where the structure is initialized. The cleanup routine starts in `client_fid_fini(..)` which then calls `seq_client_fini(..)`. These two functions decrement the appropriate reference counts on other structures and free up the memory allocated to the `lu_client_seq` structure.

There are only two other functions exported by the `fid` module: `seq_client_get_seq` and `seq_client_alloc_fid`. The `seq_client_get_seq` function is mainly used by the OSP subsystem when requesting a new sequence number that will be used for precreating objects. The `seq_client_alloc_fid` function is used to request a new FID from the client's currently allocated sequence. If the FID values in the current sequence are exhausted, a call is made to `seq_client_alloc_seq` to request a new sequence number.

Source Code 26. Function seq_client_init used in fid module initialization

```
void seq_client_init(struct lu_client_seq *seq, struct obd_export *exp,
                     enum lu_cli_type type, const char *prefix,
                     struct lu_server_seq *srv)
{
    ...
        seq->lcs_srv = srv;
        seq->lcs_type = type;
        mutex_init(&seq->lcs_mutex);
        if (type == LUSTRE_SEQ_METADATA)
                seq->lcs_width = LUSTRE_METADATA_SEQ_MAX_WIDTH;
        else
                seq->lcs_width = LUSTRE_DATA_SEQ_MAX_WIDTH;
        /* Make sure that things are clear before work is started. */
        seq_client_flush(seq);
        if (exp) seq->lcs_exp = class_export_get(exp);
        snprintf(seq->lcs_name, sizeof(seq->lcs_name), "cli-%s", prefix);
    ...
}
```

For the sequence controller and sequence manager nodes, the `fid` kernel module includes code from three additional files: `fid_handler.c`, `fid_store.c`, and `fid_lib.c`. The `fid_lib.c` file defines some special sequence ranges and reserved FIDs. The `fid_store.c` file contains functions used to persist sequence information to backend storage. The functions defined in this file are not exported by the module and are just used internally by the code in `fid_handler.c`. The `fid_handler.c` file contains the functions used by FID servers to handle requests from FID client for sequence number allocations. The `fid` module entry/exit points (`fid_init()` and `fid_exit()`) make calls to `fid_server_mod_init()` and `fid_server_mod_exit()` to handle server-specific intialization and cleanup. Server requests are handled by the functions `seq_server_check_and_alloc_super()` and `seq_server_alloc_meta()`.

7.2 FID Location Database (FLD)

Since no two storage targets ever share the same sequence numbers, a client can determine the location of an object based on the sequence number in the object's FID. To do this, a lookup table that maps sequence numbers to storage tartgets must be maintained. This lookup table is called the FID Location Database (FLD). The full FLD is stored on MDT0, but each Lustre server will maintain a subset of the FLD for the sequences assigned to it. Clients can send queries to a server to request a FID lookup in the server FLD. The response is then added to the client's local FLD cache to speed future lookups.

The code related to FLD is contained in the `lustre/fld` directory. The `fld` kernel module is built from the following source files:

- `fld_internal.h` - Contains structure definitions for FLD caching (as well as the function declarations used in the other `*.c` files.
- `lproc_fld.c` - Defines functions for debugfs support.

- `fld_cache.c` - Defines functions for caching results of FLD lookups on clients. These functions are only for internal use and are not exported by the module.
- `fld_request.c` - Defines module entry/exit points (`fld_init()` and `fld_exit()`) as well as the function used for looking up FLD entries (`fld_client_lookup()`).
- `fld_index.c` - Included only by FLD servers. Defines functions for managing the FLD database itself. Only the `fld_insert_entry()` function is exported for external use. All the other functions in this file are for internal use by the `fld` module.
- `fld_handler.c` - Included only by FLD servers. Defines the functions needed to handle FLD queries from clients.

7.3 Object Index (OI)

The Object Storage Device (OSD) layer acts as an abstraction between the MDT/OST layers and the underlying backend file system (ldiskfs or ZFS) used to store the actual objects. Although Lustre may use FIDs to reference all objects, the backend file system does not. It is the responsibility of the OSD abstraction layer to convert a Lustre FID into a storage cookie that can be used by the backend file system to locate the desired object. The term "storage cookie" is used to represent some identifier that is specific to the type of backend file system being used. In the case of ldiskfs, the storage cookie consists of the file system inode and generation number and is encapsulated in the `osd_inode_id` structure shown in Source Code 27.

Source Code 27. `osd_inode_id` structure (osd-ldiskfs/osd_oi.h)

```
/*
 * Storage cookie. Datum uniquely identifying inode on the underlying file
 * system.
 *
 * osd_inode_id is the internal ldiskfs identifier for an object. It should
 * not be visible outside of the osd-ldiskfs. Other OSDs may have different
 * identifiers, so this cannot form any part of the OSD API.
 */
struct osd_inode_id {
        __u32 oii_ino; /* inode number */
        __u32 oii_gen; /* inode generation */
};
```

The OSD layer must maintain a mapping between Lustre FIDs and the corresponding storage cookie. This mapping is referred to as the Object Index (OI). For ldiskfs, OI-related functions are declared in the header file `lustre/osd-ldiskfs/osd_oi.h` as shown in Source Code 28. The functions themselves are defined in `lustre/osd-ldiskfs/osd_oi.c`. The OI is implemented using the Index Access Module (IAM) functions defined in the `lustre/osd-ldiskfs/osd_iam.*` source files. For the ZFS backend, similar functionality is provided by code in `lustre/osd-zfs/osd_oi.c` although the implementation details differ from osd-ldiskfs.

Source Code 28. Functions for interacting with the Object Index (OI)

```
int osd_oi_init(struct osd_thread_info *info, struct osd_device *osd,
                bool restored);
void osd_oi_fini(struct osd_thread_info *info, struct osd_device *osd);
int  osd_oi_lookup(struct osd_thread_info *info, struct osd_device *osd,
                   const struct lu_fid *fid, struct osd_inode_id *id,
                   enum oi_check_flags flags);
int  osd_oi_insert(struct osd_thread_info *info, struct osd_device *osd,
                   const struct lu_fid *fid, const struct osd_inode_id *id,
                   handle_t *th, enum oi_check_flags flags, bool *exist);
int  osd_oi_delete(struct osd_thread_info *info,
                   struct osd_device *osd, const struct lu_fid *fid,
                   handle_t *th, enum oi_check_flags flags);
int  osd_oi_update(struct osd_thread_info *info, struct osd_device *osd,
                   const struct lu_fid *fid, const struct osd_inode_id *id,
                   handle_t *th, enum oi_check_flags flags);
```

8. REFERENCES

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