Version 1.5 Q1 2008

LECTURE 4.1
Lustre Architecture

Contents

- LNET
- Ext3
- DLM
- I/O protocol
- Metadata protocol
- Configuration protocol
- Recovery
- OST / MDT disk layout

LNET

More information

- The history of LNET is Sandia Portals
- There is a good manual for the portals API
  - http://sourceforge.net/sandiaportals
- LNET is a message passing API

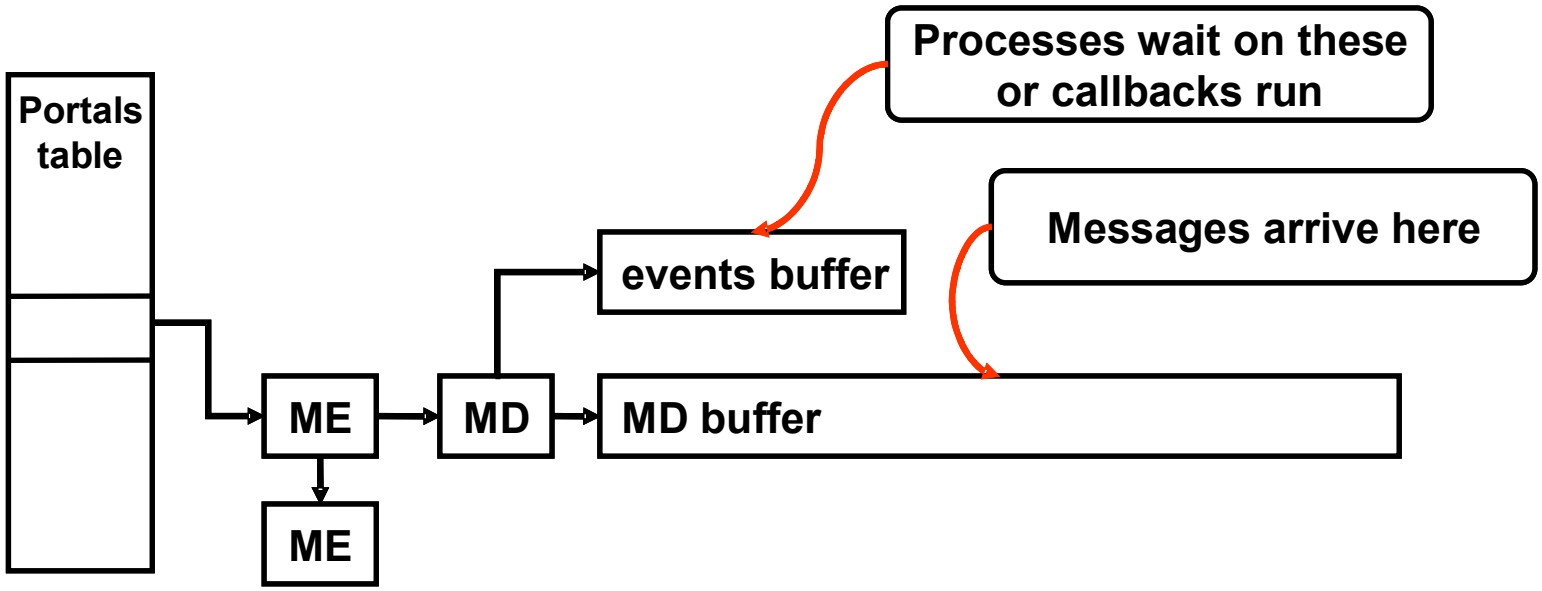
Fundamental data structures

- Destination of msg: `lnet_process_id_t` is a pair (nid, pid)
- Events: `lnet_handle_eq_t` points to buffer with `lnet_events`
- Memory Descriptor `lnet_md_t`: points to buffer, length, EQ
- Delivery indication: specify portal & matchbits when sending

- Delivery analysis: `LNetMEAttach` – attach match entry to MD
  - Portal identifier: labels a collection of match entries
  - ME's are traversed upon receipt
  - ME's point to a receiving MD

- Delivery notification: write event in event queue buffer
  - MD can point to event queue (EQ)
  - EQ points to a buffer
  - Buffer will receive `lnet_event_t` structures & callback runs
  - `LNetEQWait` waits on an event arriving in a queue

Receiving an LNET message



Lustre connections, MDs and MEs

- Connection is a structure:
  - peer_nid
  - Lustre specific data
  - xid is a per connection integer labeling requests
- MDs
  - Request buffers – a pool that grows
  - Reply buffers – individual buffers
  - All buffers are allocated before use
    - Interesting hackery to handle request buffer overflow
- Requests & reply carry the xid as matchbits
  - Request buffers ME: not sensitive to what xid is sent
  - Reply buffers ME: match exactly on xid
  - Bulk transports gets MD on the fly

Lustre event queues

- A thread can wait on an event queue
  - Similar to select system call
  - Waits for events
- Events that are used
  - Events for incoming buffers
    - Waiting for Lustre requests
    - Waiting for Lustre replies
    - Waiting for bulk data
  - Events for buffers that have “left” the node
    - Sometimes they can be freed
  - Events for ACK messages
    - Replies are sometimes ACK’ed for recovery reasons

Error handling

- LNET detects some errors
  - When it does it lazily frees the buffers
    - Buffers may be used by DMA engines
  - Lazily means through events
- Lustre detects all errors
  - Some are timeouts
  - Others are reported by LNET

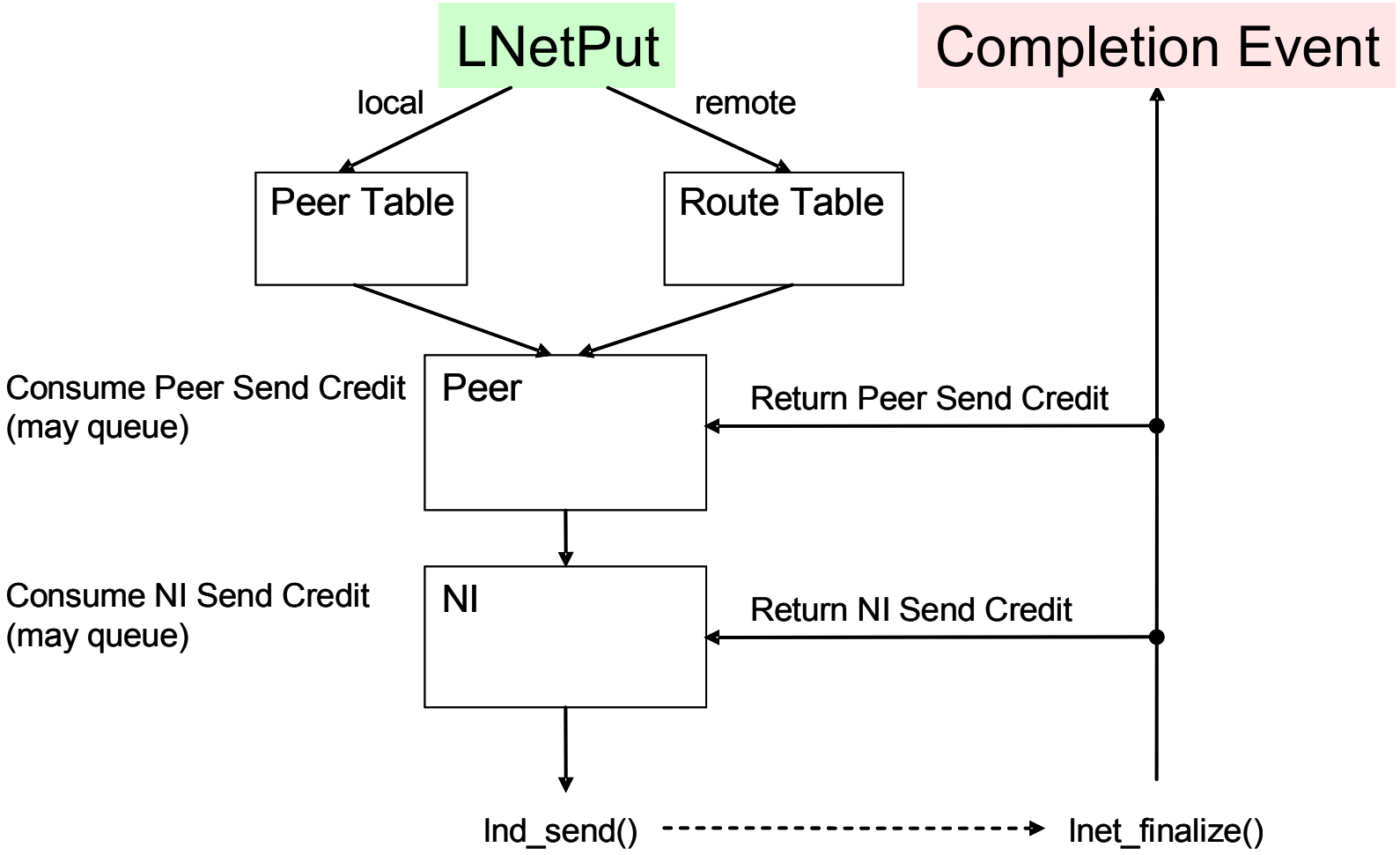
LND – Lustre network drivers

- Lustre Network Drivers
  - NAL's in Portals speak
- Lustre sees, i.e. LNET exports, only one "interface"
- Initialization is based on /etc/modules.conf
- There are ~ 10 LNDs
  - 4x IB flavor, Elan, Myrinet, TCP, 2 Cray LNDs
- So what does an LND do?

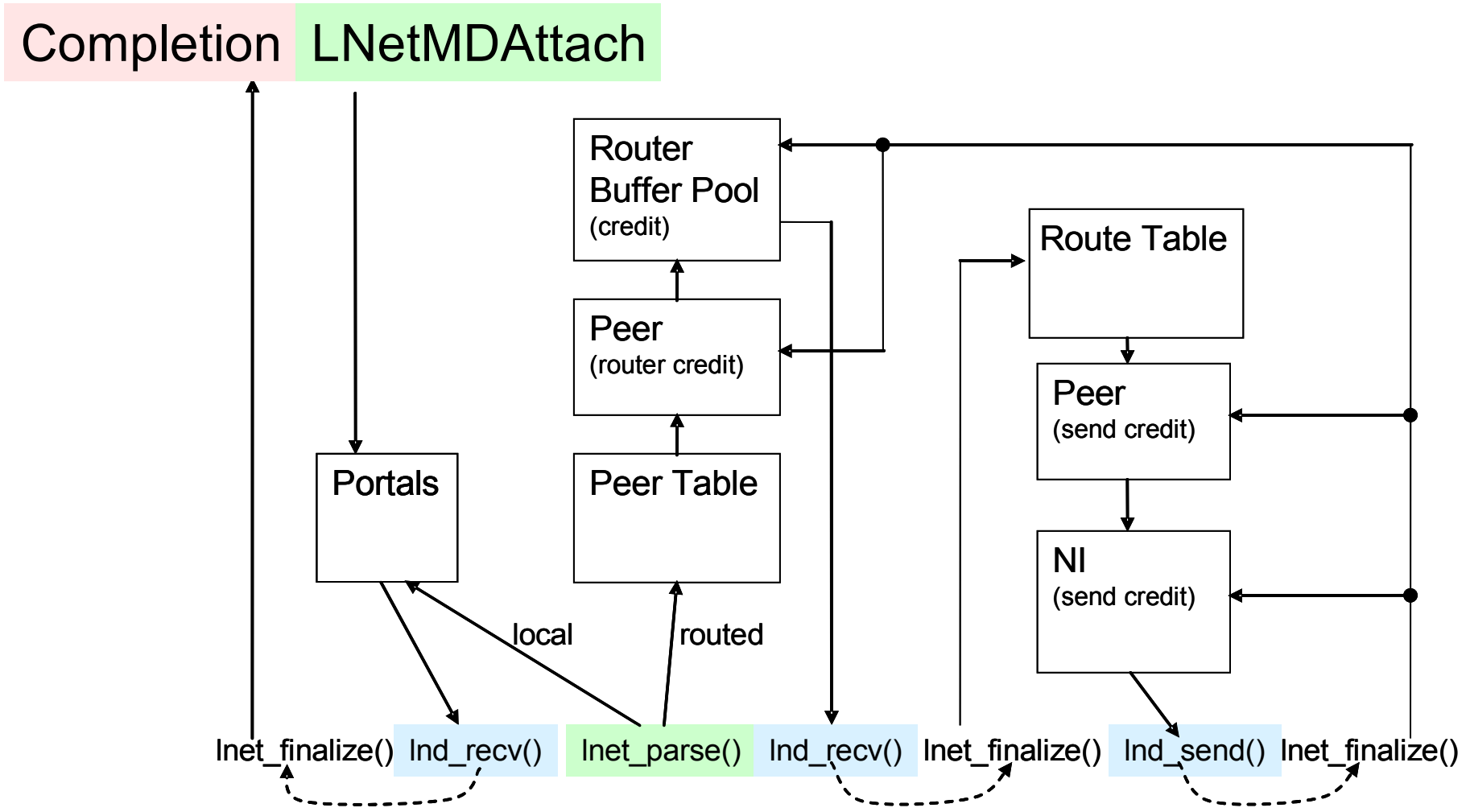
LND internals

- Implements a method table, called by LNET
  - lnd_*
  - Equally important reverse API, lnet_* called by the LND
- E.g., lnd_send – put a message on the wire
  - Can involve a DMA handshake
  - Or managing TCP transmit buffer space
- Most LNDs maintain “connection” information
  - E.g., for TCP this points to the sockets we use
  - For DMA capable NALs send/rcv credits

Outgoing Message



Incoming Message



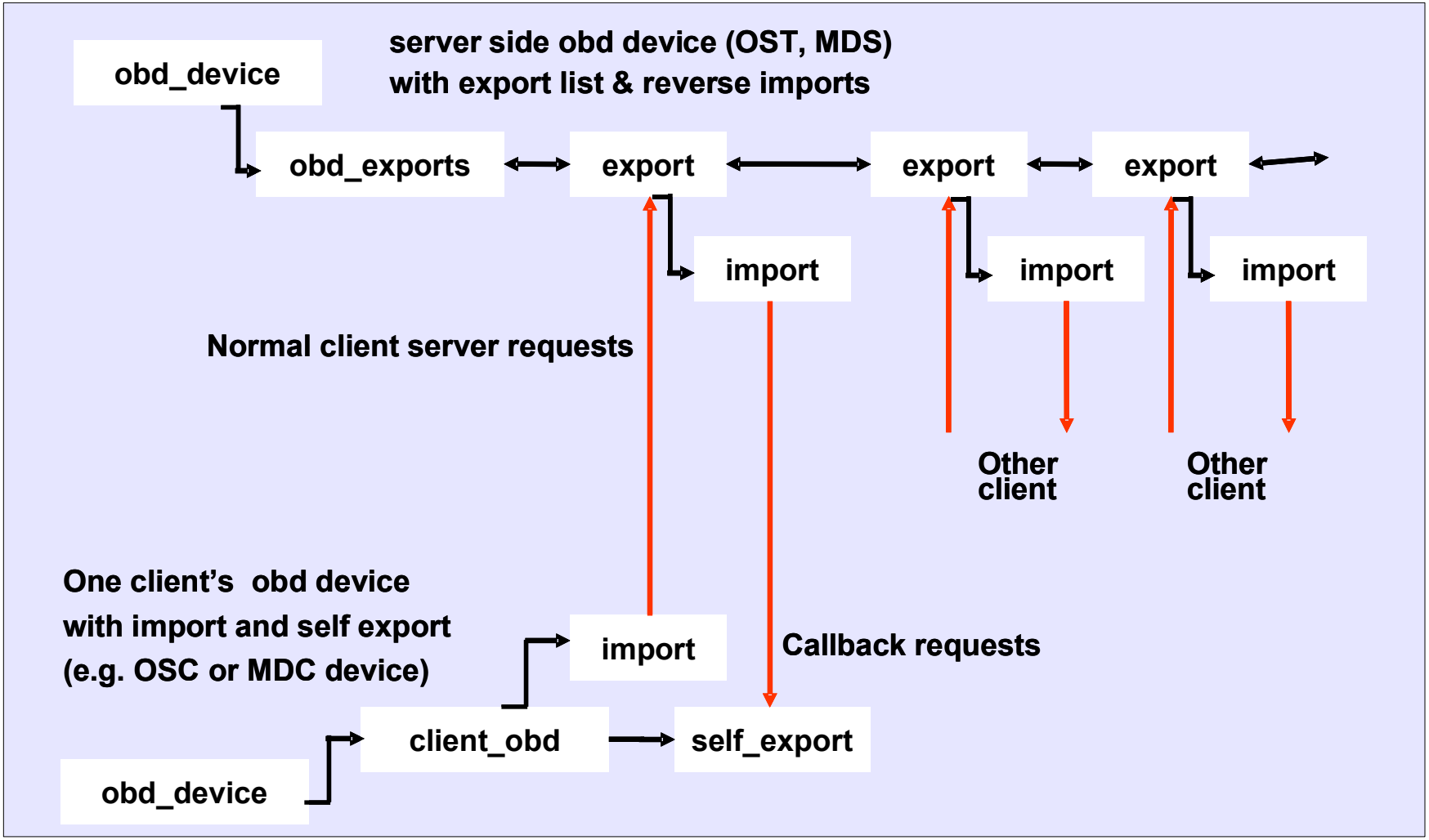
lrpc – Lustre RPC

- Used to be called ptlrpc
- Basic mechanisms to:
  - Send requests from import, receive replies
  - Receive and process requests on export, send replies
  - Including bulk transport between request and reply
- Recovery
  - Establish connections – establish import / export pair
  - lrpc will re-send requests that need recovery
  - Recovery state is managed on an import – export pair
- This involves:
  - Buffer handling – particularly request buffer management
  - Error handling – manage the state of an import/export

Generic lrpc function library

- Generic connect / disconnect
  - client_connect_import(…)
  - target_handle_connect(…)
  - target_handle_reconnect(…)
- A request set handler
  - Handle multiple requests asynchronously
- A ping infrastructure
  - For health / liveness checks
- A bulk llog callback handlers
  - Collect pages of cookies and send across

Exports & Imports for RPCs



Request processing

- Client – allocate request and reply buffer
- Fill request buffer
- Call lrpc_queue_wait

Recovery

- Much of recovery takes place in lrpc!

- Resending requests
- Reconnecting
- Pinging
- Server waiting for clients to join for recovery
- Processing a queue of replay / resend requests

Ext4 & ldiskfs

Ext3 & ldiskfs

- Ext4 is a fork of Ext3 - too many changes (from CFS)
- ldiskfs is the Lustre version of ext4
- Sometimes equal to ext4, usually ahead of ext4

- In this section we will describe
  - Recent ext4 enhancements originating in Lustre
  - Special use of ext4 by Lustre

Allocation with extents

- Filesystem extent
  - Contiguous on-disk & in-file area
  - Triple (StartBlockInFile, StartBlockOnDisk, BlockNumbers)
  - Benefits
    - Make allocation MD (“mapping”) much smaller
    - Speedup truncate and metadata overhead
- Extent library used in other places
  - Snapshots
  - Hierarchical stripe descriptors

Extents

- Critical data structures
  - struct ext3_extents_tree
    - Extents mappings of a whole file
  - struct ext3_extent
    - Mapping of a piece of contiguous file area
  - struct ext3_extent_idx
    - Used inside the htree
- Extent allocation policy
  - Always try to allocate N contiguous blocks

mballoc - the block allocator

- Old allocation style
  - Per block, not contiguous extents of free blocks
  - Needed lock_super()
  - Too much linear scanning on bitmaps
- Mballoc design
  - Buddy bitmap:
    - Buddy block describe 2^N contiguous blocks, where N>=0
    - In addition, there is the existing block bitmap
  - Allocation of extents of size 2^N
    - Is efficient, and aligned
  - Refined locking - avoid the super block lock, per cpu locks
  - Keep files that are expected to be small close together

Allocation policy

- Three mechanisms
- Goal
  - Write behind the previous data if possible
- Large I/O policy
  - Write the data in a contiguous block anywhere
    - I/O is large enough to eliminate seek overhead
  - Physical and logical alignment (mod X Mb)
- Small I/O policy
  - Keep small chunks close together, close to inode
    - Like ext3
- Writing a large file with small synchronous files hurts
  - Fixed with an OSS cache

Transactions

- Lustre frequently nests transactions
- E.g., in mds_reint_unlink
  - Start a transaction (fsfilt_start_{log})
  - Unlink the inode (vfs_unlink)
  - If it is open, put it in the orphan directory (mds_orphan_add_link)
  - Add an llog entry (mds_log_op_unlink)
  - Set the parent mtime/ctime (fsfilt_setattr)
  - Finish the transaction (fsfilt_finish_transno)

Commit callbacks

- When disk data commits, run something else
- E.g., OST commits objects destroy
  - Then it's time to cancel the MDS llog records
  - Add the cookies to the llog cancel page
  - … truncate the object
  - Start a transaction (fsfilt_start_{log})
  - Remove the object (filter_destroy_internal)
  - Add the commit callback (fsfilt_add_journal_cb)
    - CB is filter_cancel_cookies_cb
  - Finish the transaction (fsfilt_finish_transno)

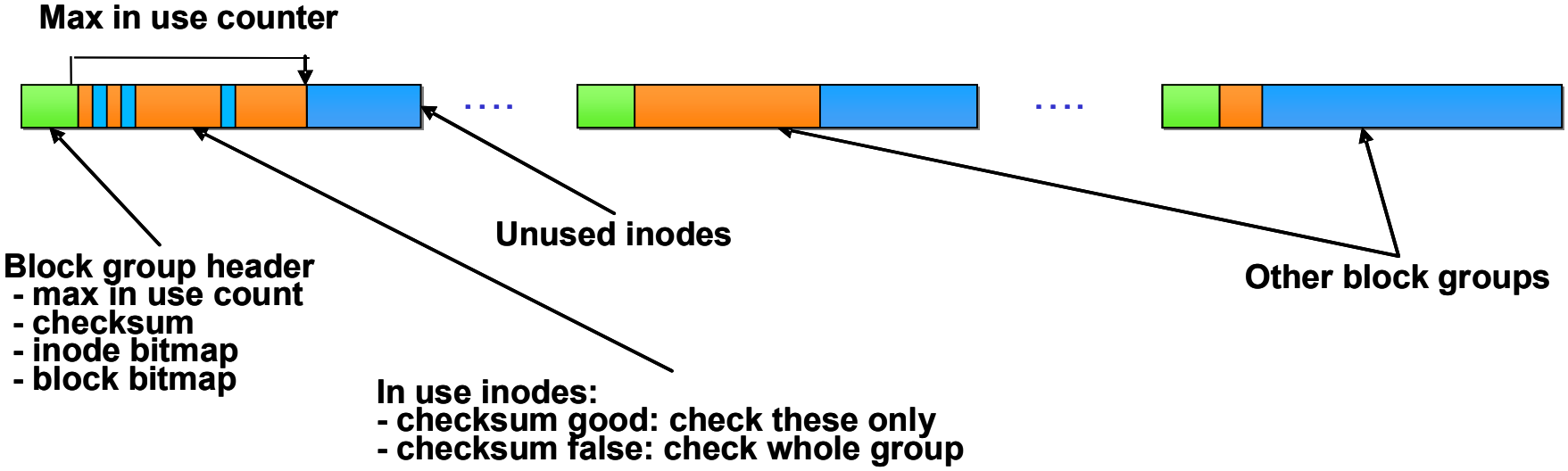
I/O in the OST

- The page cache made things too slow in Linux 2.4
- Reserved memory registered for DMA can help

- OSS does non-cached direct IO
  - > Nothing ends up in the OSS page cache
  - > We expect to resurrect an OSS page cache
    - – Certainly for reading small files back
    - – Maybe for dirty data in conjunction with liblustre

Fast FSCK & Format

- FSCK has changed
  - Previously fsck scanned all inodes
  - Now only inodes that are possibly in use
- The most interesting part of this is a checksum
  - The checksum indicates if the metadata that follows is consistent
  - If it is the counter can be used to check up to the maximum inode
- Speedups of 4x to 10x
  - Good, but fsck needs to disappear completely, it doesn't scale



Lustre DLM

Terminology

- A lock protects a resource
- A client enqueues a lock to get it
- An enqueued lock has a client and server copy
- Servers send blocking callbacks to revoke locks
- Servers send completion callbacks to grant locks
- Processes reference granted client locks for use
- Processes de-reference client locks after use
- Clients cancel locks upon callbacks or LRU overflow
- Callbacks were called AST's in VAX-VMS lingo
- Cancel was de-queue in VAX-VMS lingo

- Typically a lock protects something a client caches

History

- Basic ideas are similar to VAX DLM
  - You get locks on resources in a namespace
  - All lock calls are asynchronous and get completions
  - There are 6 lock modes with compatibility
  - There are server to client callbacks for notification
  - There are master locks on the “server” and client locks
- Differences
  - We don’t migrate server lock data, except during failover
    - LDLM is more like a collection of lock servers
  - There are extensions to:
    - Handle intents – interpret what the caller wants
    - Handle extents – protect ranges of files
    - Handle lock bits – lock parts of metadata attributes

Client lock usage

- DLM locks are acquired over the network
  - The locks are owned by clients of the DLM
    - MGC, OSC & MDC are examples
- Use of locks
  - Locks are given to a particular lock client
  - Processes reference the locks
  - Locks can be cancelled only when idle
- Differences
  - Locks are not owned by processes (VAX)
- Servers can take locks also

Lustre Lock Namespaces

- OST: namespace to protect object extents.
  - Resources are object ids
  - Extents in the object are “policy data”
- MDS: namespace to protect inodes and names
  - FIDs are the resources
  - Lock bits are policy data
  - Intents bundle a VFS operation with its lock requests
- MGS: namespace for configuration locks
  - Presently only one resource
  - Protects the entire configuration data

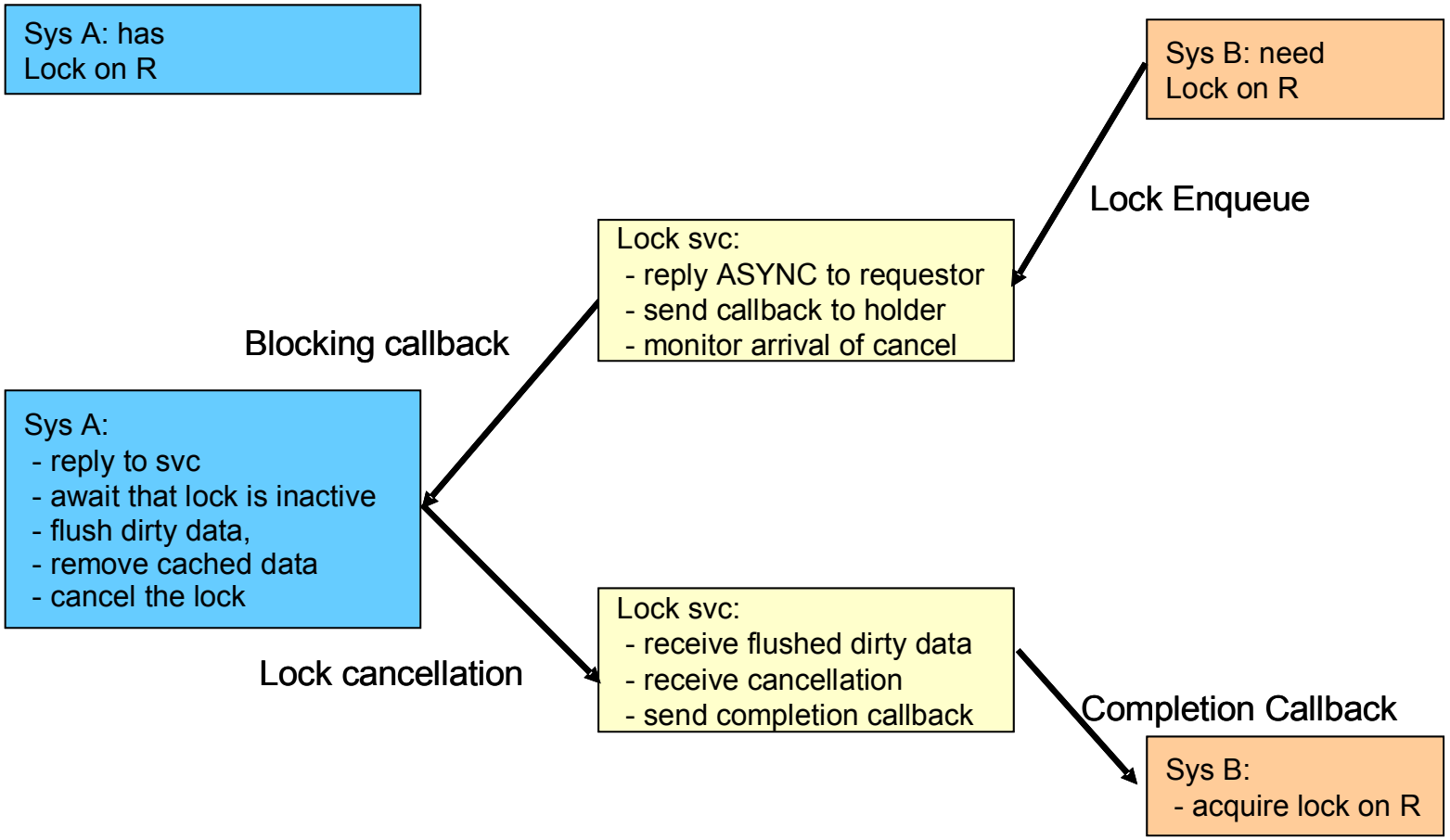
Lock modes

- A lock on a resource can be taken out in six modes.
  - EX exclusive
  - PW protected write
  - PR protected read
  - CW concurrent write
  - CR concurrent read
  - NL null

Compatibility

	NL	CR	CW	PR	PW	EX
NL	1	1	1	1	1	1
CR	1	1	1	1	1	0
CW	1	1	1	0	0	0
PR	1	1	0	1	0	0
PW	1	1	0	0	0	0
EX	1	0	0	0	0	0

Typical simple lock sequence



Locking file extents for POSIX

- Lustre extent lock
  - Lock covers an area inside file during R/W lustre file.
  - Acquired by Lustre filesystem clients for
    - R/W
    - File size computation
    - Truncation
  - Release reference on it after R/W, keep cached for quick re-use
  - Handle blocking callbacks for revocations
  - File locks broken down by LOV into lock per object
- Use
  - For data consistency R/W, and truncate
  - File size management
  - Important client constant is maintained:
    - Known Minimum Size (KMS) of each stripe
- No user API
  - Locks are referenced only within a single syscall

Extent optimization algorithm

- Motivation
  - Typical use is one client doing I/O to a file
  - Reducing lock requests for contiguous areas
    - From the same client
  - One user: one lock
- Optimization scenarios
  - Client: search the cached locks for compatible locks
    - Use cached locks – can use write lock for reading!
  - Server runs ldlm_extent_policy ()
    - Scan server granted/waiting queues
    - Calculate nearest extents in incompatible locks found
    - Grant biggest possible extent

IO and locking

- Stripe locking
  - Change from
    - Lock all stripe extents, do all IO in parallel, unlock all
  - To
    - For all stripes in parallel: lock, do IO, unlock
  - Holding locks from multiple servers
    - Can lead to cascading recovery events on many servers
    - Is necessary for truncate and O_APPEND writes
- Disallow client locks under contention
  - When an extent in a file sees concurrent access
    - Ask the client to write through to the server
  - This eliminates callback traffic and cache flushes

User controllable locks

- fcntl / flock
  - Fairly standard interface
  - Backed by DLM locks
  - Implementation feels preliminary
  - Some of our partners activate this by default
- A special group lock for MPI use
  - Allows a group of processes to exclude others
  - Can be mandatory or advisory
  - Typical use: keep visualization clients away from busy files
- Special use of locks by clustered exports of NFSv4
  - See CITI documentation

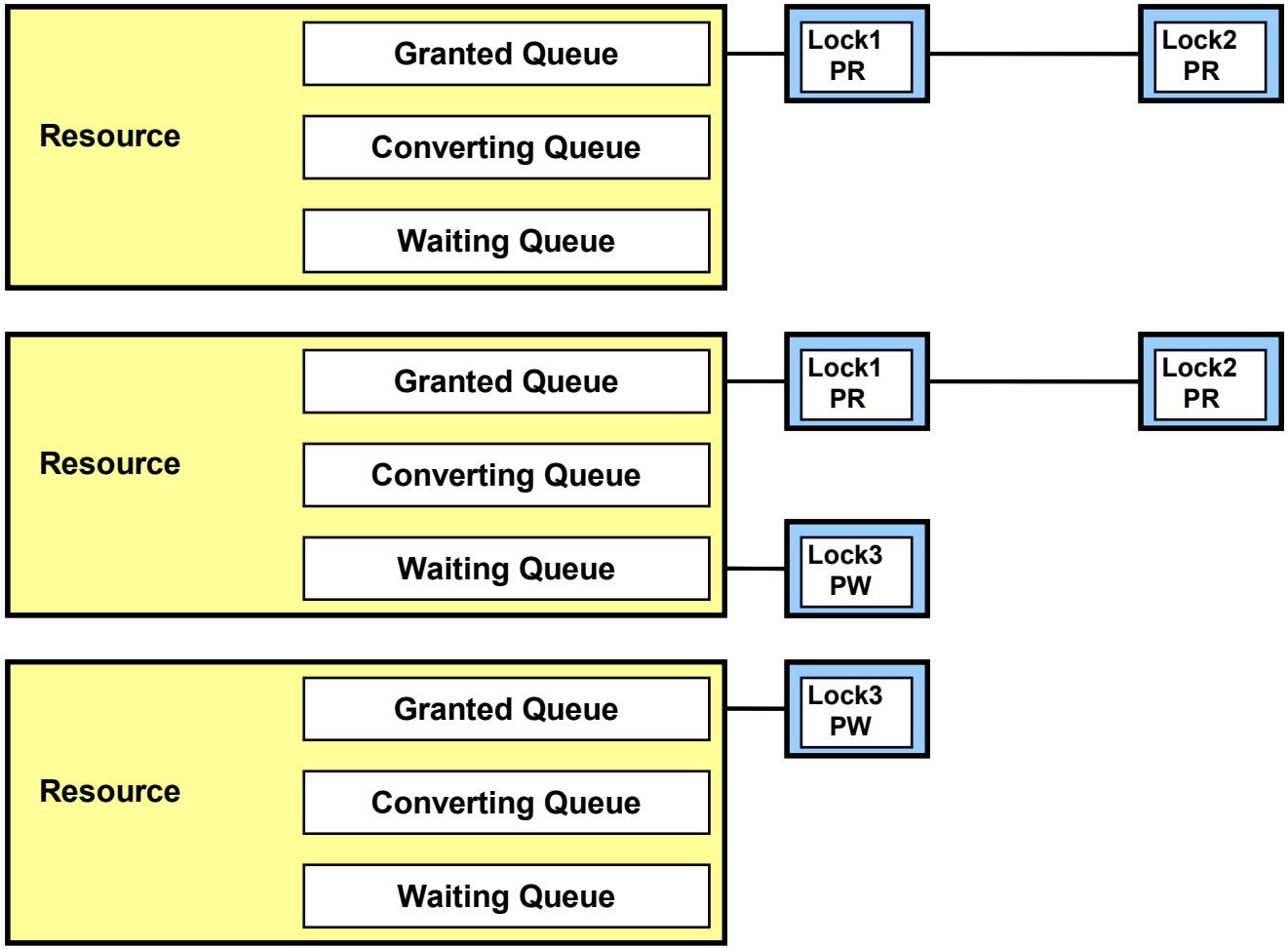
Conversion from read to write

- Motivation
  - Things would start with a read – lock
  - Cancellation of read locks would lead to cache flush
  - Conversion to a write lock allows retention of cached data
    - But it can deadlock
- Lock conversion is not used yet in Lustre
  - A version on the inodes could allow retention of cache

Client Lock callback handling

- Callback function is bound to lock
  - Upon client side lock enqueue
  - RPC's made to the client ldlm service by servers
  - Handed by client lock callback thread : ldlm_cbd
- Completion callback
  - When lock is granted or request failed AST notification
- Blocking callback
  - Called when servers try to cancel locks in clients
  - Causes cache flush
- Glimpse callback – to get file size
  - If lock cannot be granted, just give size
  - Don't flush cache
  - Cancel lock if it is not busy

Ldlm queues – processed on server

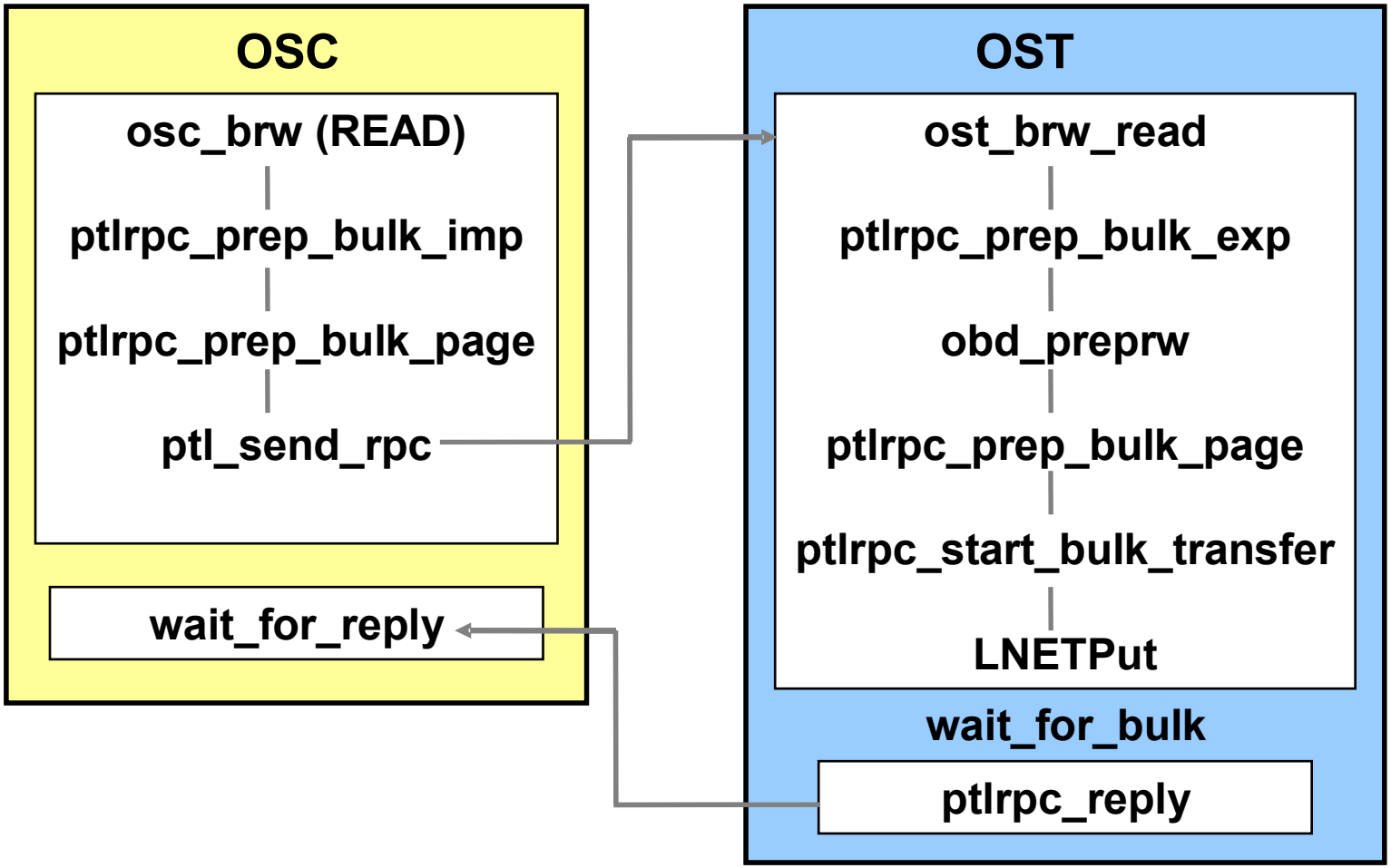


I/O protocol

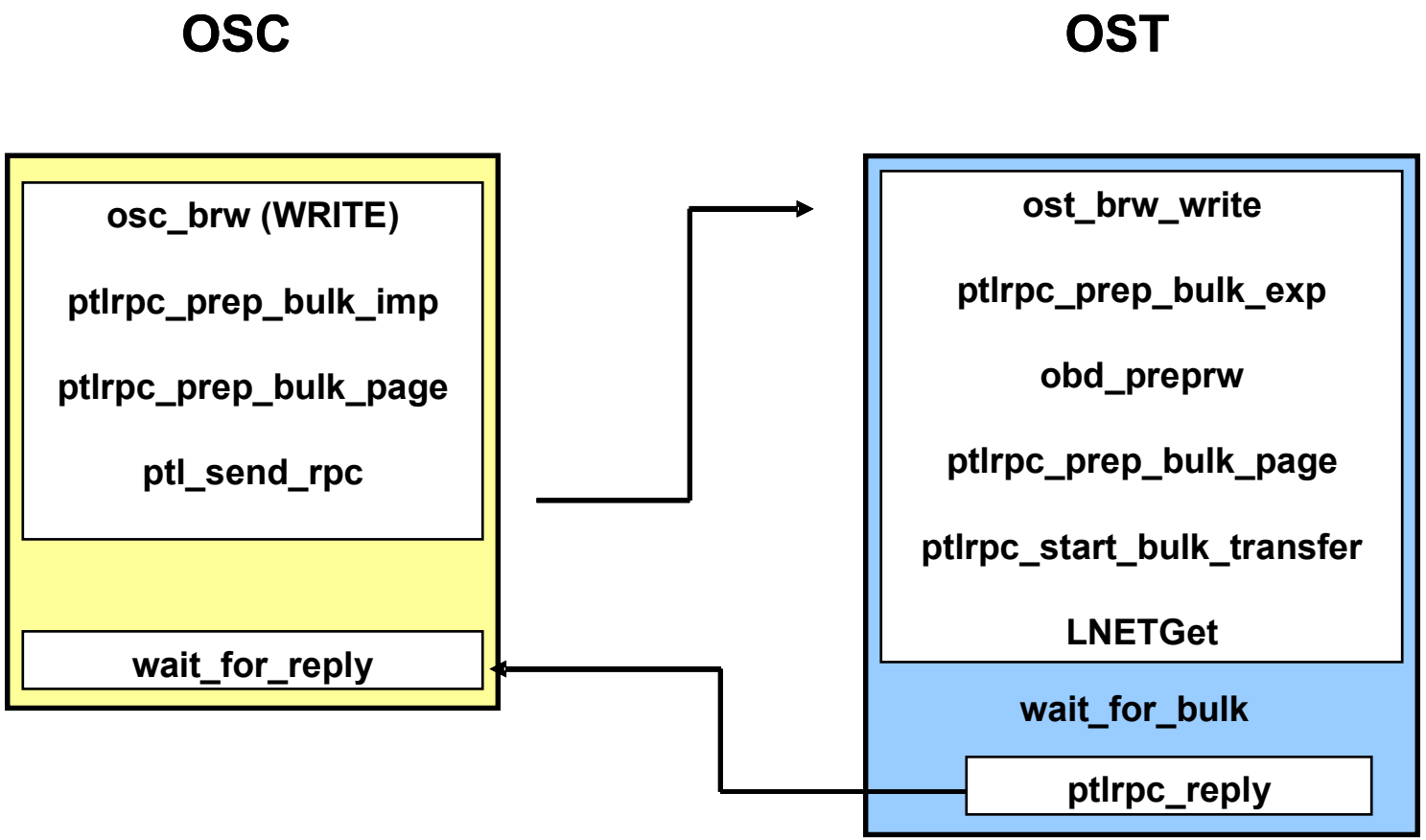
I/O from 30,000 feet

- Lustre lite
  - Dirties pages
  - Asks for pages to be flushed (fsync, etc)
- LOV directs pages to correct OSC
- OSC
  - Assembles IOV of dirty pages
  - Keeps flight groups to OST on the wire
- OST / OSD
  - Receive or send data (when possible with RDMA)
  - Perform block allocation in objects
  - Do direct I/O

osc-ost READ diagram



Osc-ost WRITE diagram



Event callbacks for bulk

- Server side callback
  - Registered in bulk preparation phase
  - server_bulk_callback() wakes up sleeping server
    - On bulk transfer completion event
  - Then server sends lrpc reply message to client
- Client side callback
  - Registered in bulk preparation phase
  - client_bulk_callback() wakes up client
    - Which is sleeping on lrpc reply from server

lrpc sets

- Infrastructure
  - ptlrpcd() kernel thread
    - Check for lrpc requests in set_requests list
    - Move new request in set_new_requests list to pc_set
    - Handle requests in pc_set with ptlrpc_check_set()
  - There are two sets: one for recovery, one for normal use
  - APIs
    - Add set requests by ptlrpcd_add_req()
    - Wait on completion of the set with ptlrpc_set_wait()
- Usage in osc_brw_async ()
  - Uses ptlrpc_set_add_req() to add async lrpc request
  - Use brw_interpret() async callback to wakeup process waiting for it

OSC page management

- Warning
  - This is likely going to change somewhat
  - Linux 2.4 forced us down the current path
- At the moment Lustre
  - Tracks all dirty pages
  - When enough are there, the OSC pushes them out
- Linux disk file systems
  - Flush pages from the page cache
  - Only then they are sent to storage
  - Lustre will move in this direction in the 1.8 timeframe

Page Queueing in the OSC

- Asynchronous OBD API
  - Benefits: batching RPC to maximize efficiency
  - Callers: commit_write() & writepage()
- Page Queueing APIs
  - Registering Page in OSC
    - API: osc_prep_async_page()
    - binding page to a new created OSC async page and set RPC callback pointers for post processes
  - Queueing Page in OSC
    - API: osc_async_page_io()
    - Using the cookie returned from Page Registering function to find the OSC async page

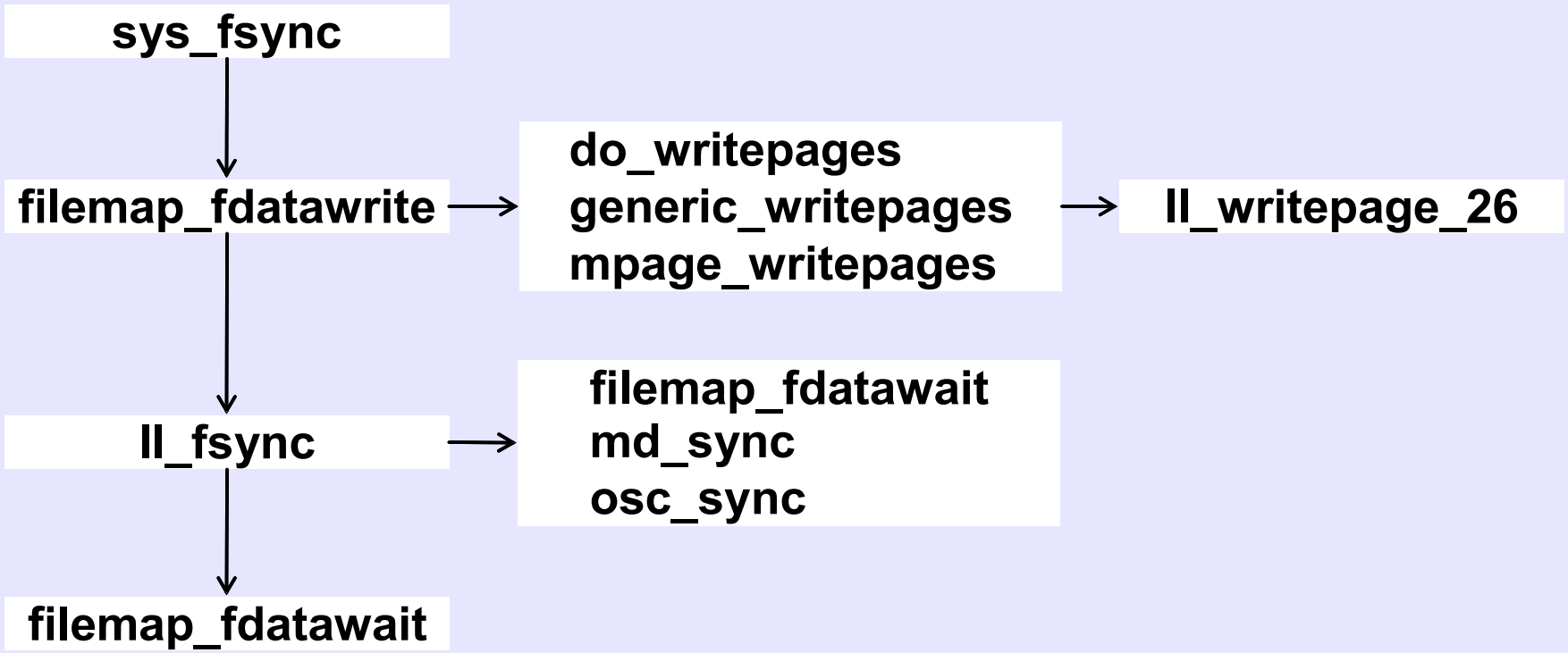
Trigger RPC when reach iov size

- APIs
  - osc_check_rpcs()
  - osc_send_oap_rpc()
- Scenarios
  - Inside osc_send_oap_rpc()
    - When constructing async RPC request
    - If OSC async page count reach cl_max_pages_per_rpc
    - Then create an async RPC request for it
  - If osc_send_oap_rpc() races with commit_write()
    - Retry 10 times before exit this RPC creation

OSC flight group management

- Client Side in flight RPCs
  - cl_brw_in_flight: in-flight RPC count
  - cl_max_rpcs_in_flight: upper limit of in flight RPCs
- Scenarios
  - When 'cl_brw_in_flight' reaches upper limit
    - Stop constructing async RPC requests
  - Without grant, one RPC only:
    - Put process to sleep when grant is below lower limit
    - Wakeup it when cl_brw_in_flight is 0
  - In-flight count
    - Increase when constructing async RPC requests
    - Decrease it when receiving async RPC reply

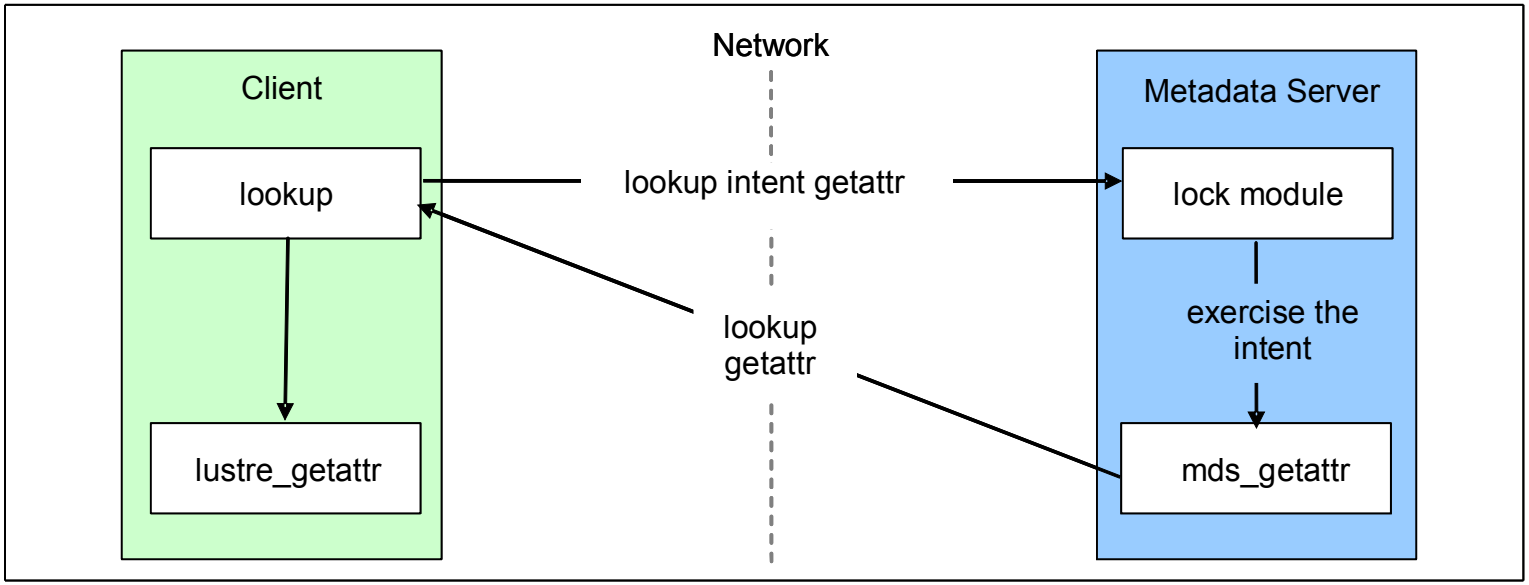
example of use fsync()



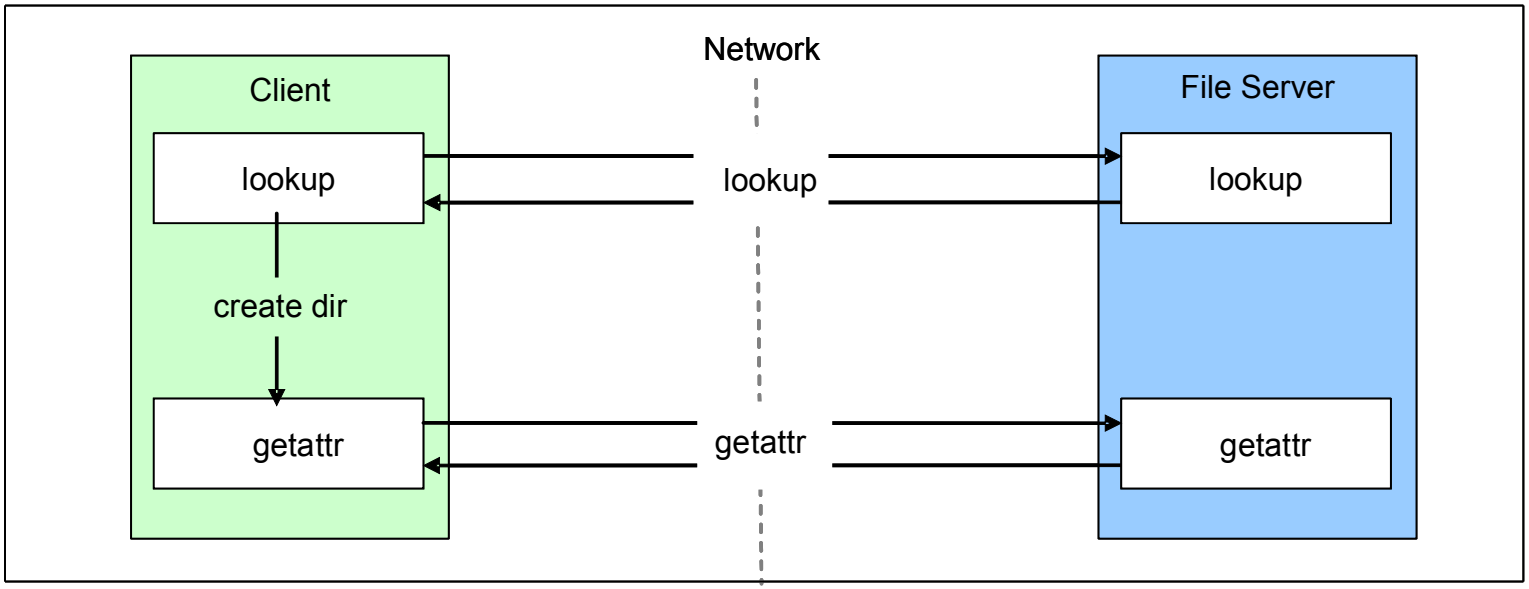
Metadata protocol

Metadata Intents

- mds_enqueue
- Client tries to acquire a lock
  - Lock manager has a policy function which looks at intent
  - Lock request contains a lot of information
    - lookup, getattr: returns inode & dentry with a lock
    - open: return inode, dentry, file handle and status
  - Interpreting the returned results on the client:
    - Key question – at what phase did an error occur?
    - Disposition – client knows what executed on server
      - Was a file created remotely? Was open executed?
    - Status – error code of last operation

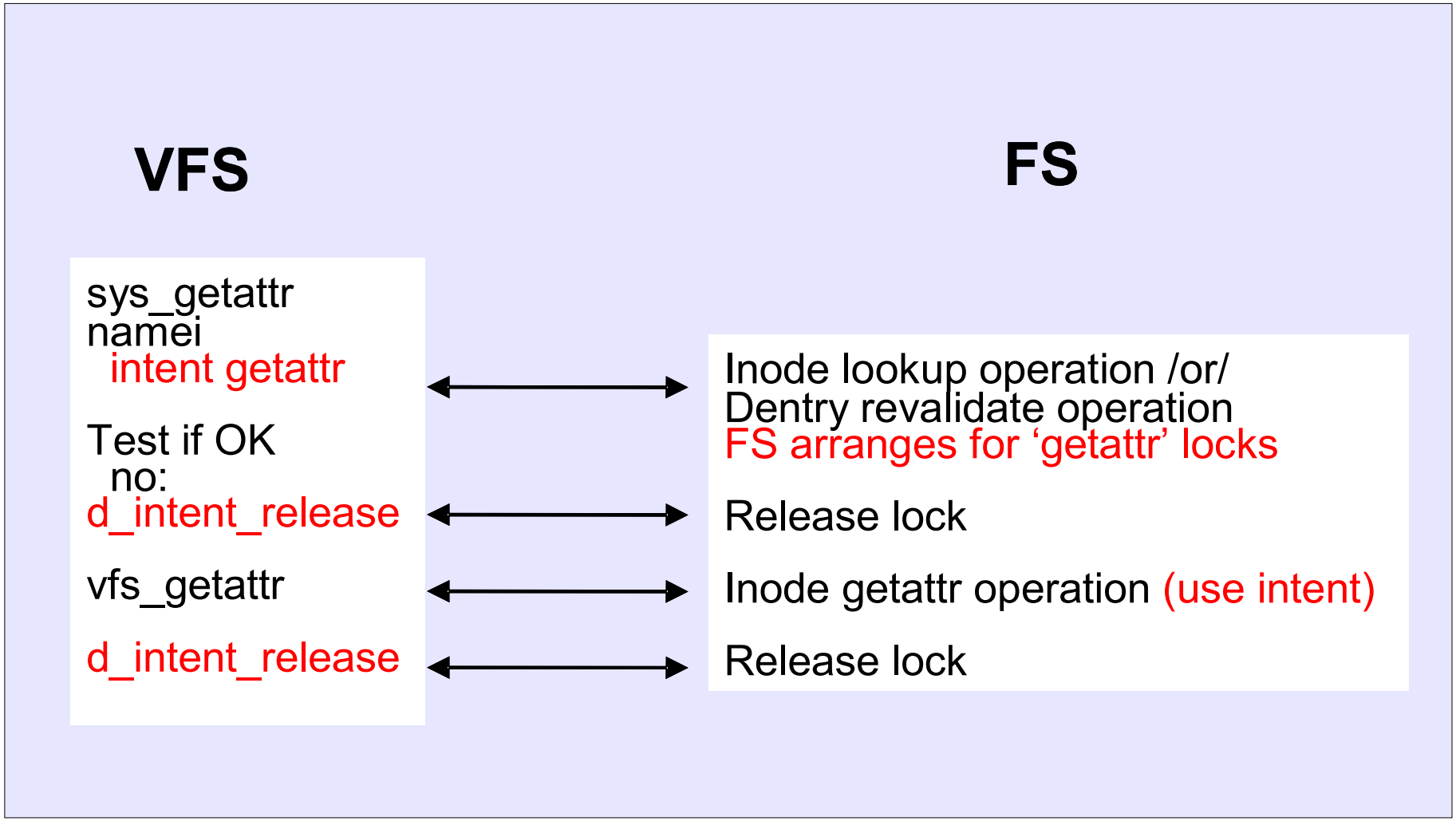


Lustre getattr



Conventional getattr

VFS Changes: Intent Lookups



Raw metadata operations

- mds_reint - raw operations
  - mkdir, unlink, rename, symlink, link, setattr
  - Arguments: parent fid(s), name(s), attrs
  - Execute operation on the server
  - Only return status
  - Do not return new namespace elements
- Much simpler to make things stable
  - More server enforced security
  - Considerably faster
- Current patchless client has no raw operations

Protocol - ctd

- mds_getattr
  - Get attributes by fid
- For revalidation of attributes of open files

Locks & Handles

- Locks used during one system call
  - During this time a lock is pinned with a refcount
  - No long living pinned locks!
  - Cached locks live long
- Open File Handles are long lived
  - Handle implemented as MDS pinned dentry
- Open files and directories
  - Have server based handles in c-s operation
  - Will have client handles during w-b caching
  - Open & Files with i_link > 1 always use server handles
- Current working directories & mtpts
  - Pinned with server handles, mtpts cannot be unlinked
  - Still not done

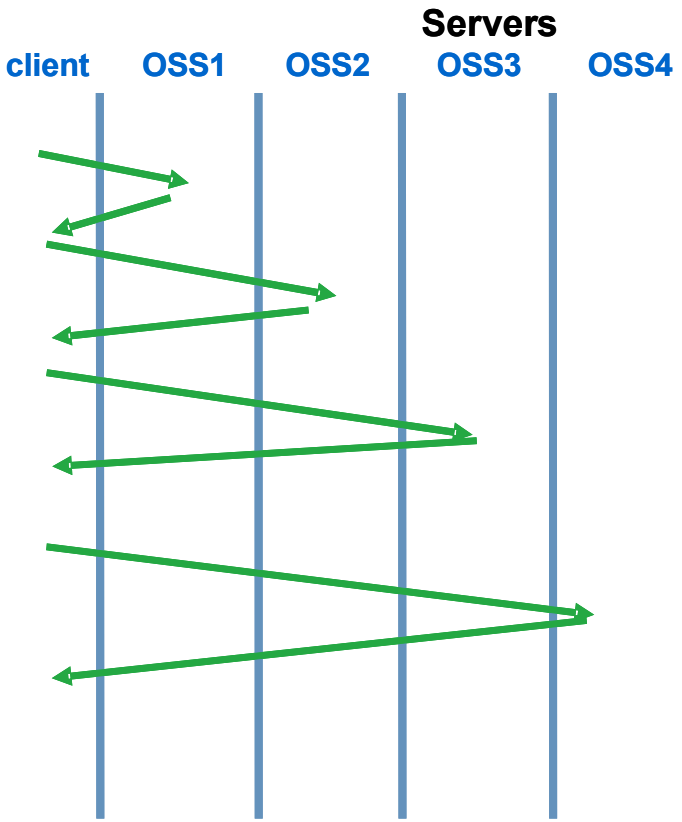
Lock bits

- Example: create many files in /lustre/dir
- Each time the client needs to lookup “dir”
  - But “dir” is changing, because files are added to it
  - A single lock would lead to lock bounces
- Separate the locks on dir inode for
  - Lookup – mode, owner, ACL
  - Updates – mtime, size, data
  - The lock request indicates what bits it wants to acquire
- Another lock bit controls opening of files
  - Lustre 1.4.7 has an open file cache.

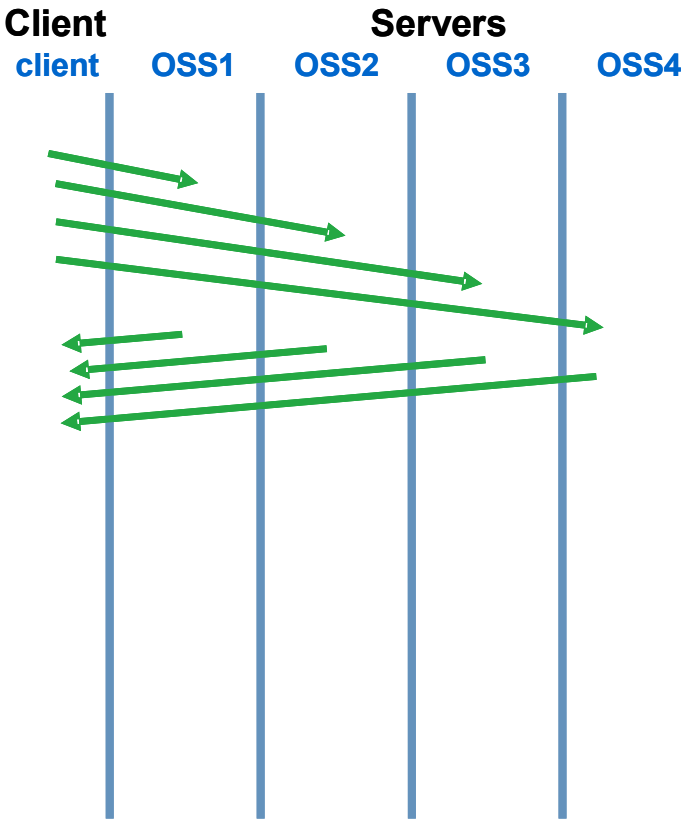
Lock bits

- Example: create many files in /lustre/dir
- Each time the client needs to lookup “dir”
  - But “dir” is changing, because files are added to it
  - A single lock would lead to lock bounces
- Separate the locks on dir inode for
  - Lookup – mode, owner, ACL
  - Updates – mtime, size, data
  - The lock request indicates what bits it wants to acquire
- Another lock bit controls opening of files
  - Lustre 1.4.7 has an open file cache.

Parallel operations



Sequential RPC's



Parallel RPC's

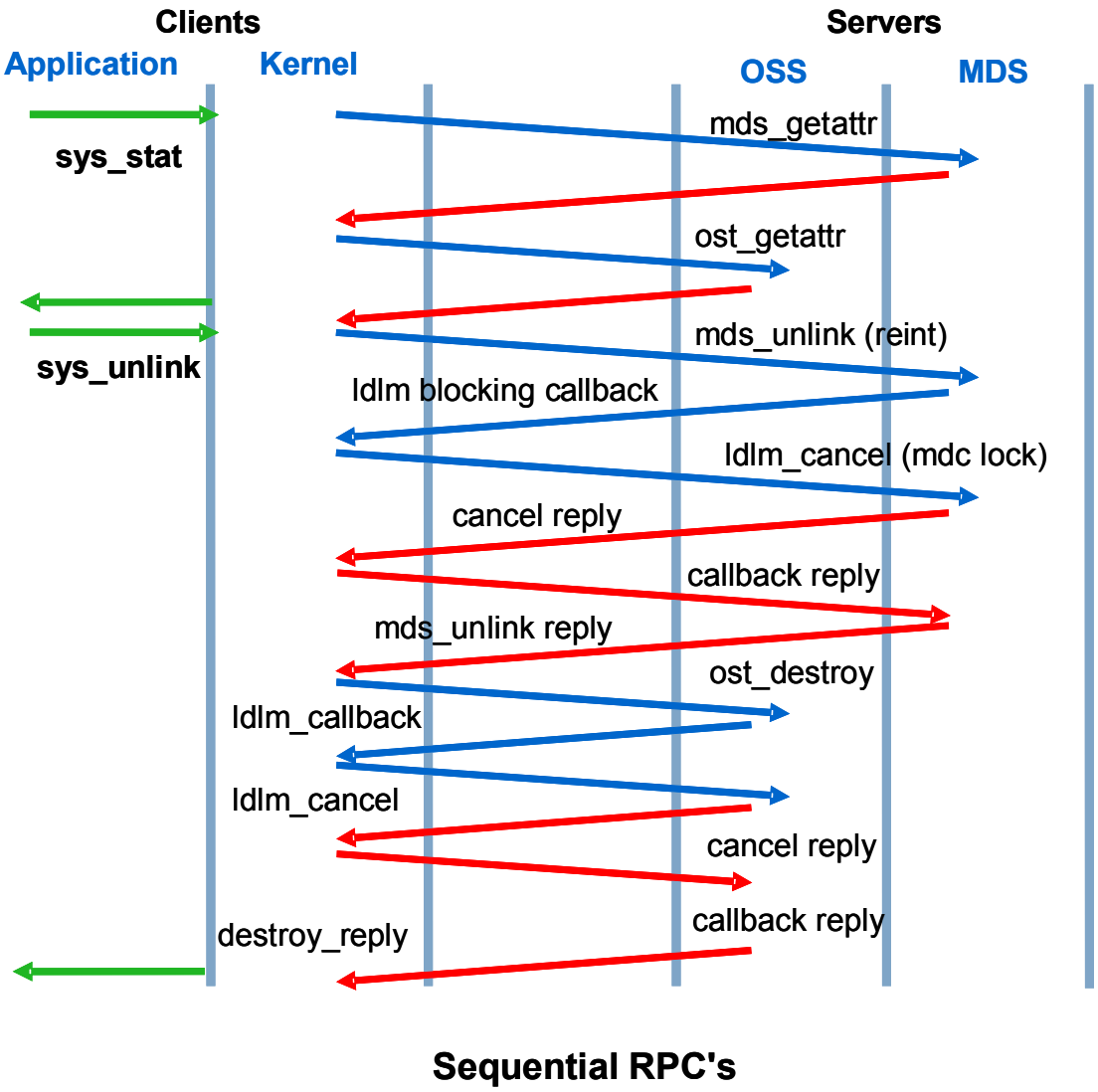
Early lock cancellation

- Clients obtain locks
  - Sometimes it is known that they will see a cancellation callback
  - Early cancellations eliminate the callback
- Performance improvement
  - Serious RPC reduction
- Use cases
  - removing files, directories
  - rename
  - link
  - updating attributes
- Example GNU “rm” file utility
  - Does a stat on the file
  - Then makes an unlink system call

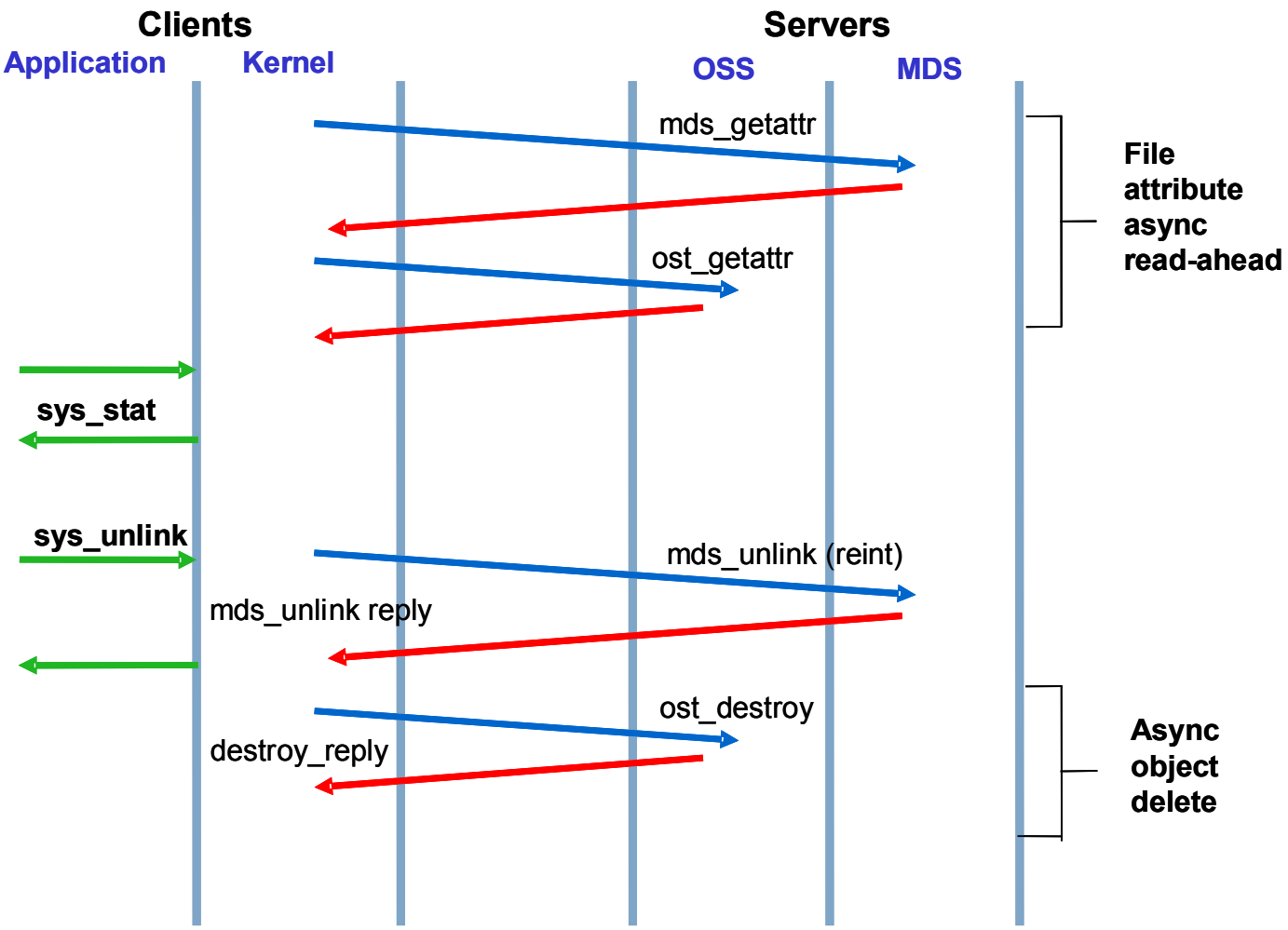
Directory & attribute read-ahead

- RPC intensive patterns
  - Read directory pages
  - Operate on all inodes in the page
- Attribute read-ahead:
  - Fetch attributes from MDS and OSS in the background
- Common use cases
  - List all files in a directory
    - readdir
    - get mds inode attributes
    - get oss object attributes
  - Remove all files in a directory
    - readdir
    - get mds inode, oss object attributes
    - unlink inode, object

Common “rm file” – wait for 8 RPCs



Sequential RPC's



Early lock cancellation

Configuration protocol

obd devices

- Lustre consists of 3 types of modules
  - Lustre (obd) devices – accept API calls
    - LOV, OSC, MDC, obdfilter
  - Server devices – translate network to Lustre api
    - OST, MDT
  - Applications – use Lustre API calls
    - lustre client and liblustre client
  - Each device has configuration operations
  - attach – a name is associated with the device
  - setup – the device is made ready for use
  - connect – the device begins to use other devices
    - Connect overloads network and local connections
  - Of course, there is disconnect, cleanup, detach

Lustre API

- Implemented as method table for obd_device
  - Reasonable amount of sharing
  - Should split into multiple tables
- Several different kinds of methods:
  - Object API – create objects, do IO, manage attributes
  - MD API – metadata operations
  - Locking – mostly embedded in object / MD api
  - Management API – attach, setup, connect
  - Recovery related API
- Some cleanup of this can be expected in due course

What does configuration do?

- Configuration
  - With lconf in 1.4
  - With mkfs / mount through the MGS in 1.6
- The MGS writes a sequence of records in a llog file
  - The records contain commands with arguments for:
    - New device, Attach, Setup, Connect etc.
    - Every log record contains a sequence number, date & version
- Servers read this log from the disk
- Clients fetch this log over the network
  - Nodes can also re-fetch and process all updates

More on mountconf

- Formatting a server leaves some options behind
  - In particular a flag “first mount” and a flag “needs index”
- During a first mount of a server
  - The server offers its configuration to the MGS
  - The MGS adds new records to the llog
  - The MGS tells the new server its sequence number
    - The new server updates the disk label on the partition
  - The MGS revokes a configuration lock
  - All other nodes in the cluster learn about the new server
- More details about this will be discussed later in the course

Llog processing

- Llogs have method tables
  - Quite abstract to use logs very generally
- There is a general iteration function
- On clients this iteration function
  - Reads 8K pages of the llog from the server
    - Same function that reads directory data!
  - Processes the records in the pages
  - Continues (as long as the callback function exits with 0)

Configuration lock

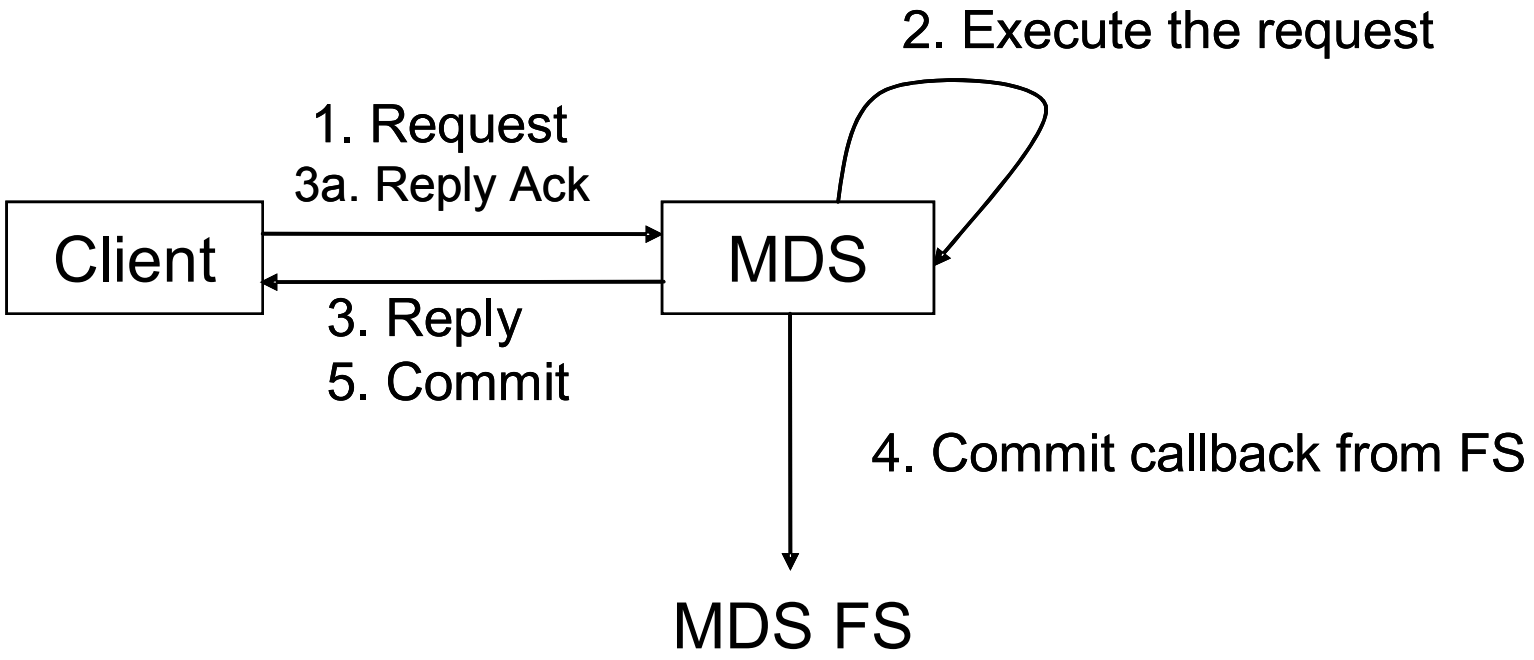
- The central configuration server is the MGS
- When a client fetches a log it also gets a lock
  - The lock gets callbacks when the configuration changes
- Callback triggering events
  - Online addition of OST devices
  - Setting timeouts is global now
  - Many others will follow (snapshots, policy dispatch)
  - More robustness fixes

Lustre Recovery

Aspects of Recovery

- Disk file systems need recovery
  - Not discussed here
- Routers may crash - must be avoided
  - Not discussed here
- Servers roll back when they crash
  - Clients will try to rebuild the server state
- Open (maybe unlinked) files need re-opening
- Inode - Object relationship can go bad
  - Objects without file inodes need cleanup
- File size synchronization from OSSs to MDS
- Clients can crash - servers need to clean up state
- Recovery aims to restore globally consistent state

Request lifecycle



MDS execution

- MDS executes transactions
  - In parallel by multiple threads
- Two stage commit:
  - Commit in memory – after this results are visible
  - Commit on disk – in same order but later
  - This batches the transactions
- Key recovery issue
  - Other CFSs commit synchronously
  - Lustre MDS can lose some transactions
  - Clients need to replay in precisely same order

Client MDS interaction

- Send request
- Request is allocated a transno
- Send reply which includes transno
- Clients acknowledge reply
  - Purpose: MDS knows clients has transno
- Clients keep request & reply
  - Until MDS confirms a disk commit
  - Purpose: client can compensate for lost trans
- MDS has disk data per client
  - Last executed request, last reply information

What happens during recovery?

- Clients reconnect to the MDS
- MDS reports the last transno it committed
- Replay - resending requests that have replies
  - Clients resend requests including transno's
  - MDS merges & sorts them to get correct sequence
- After replay only a few requests remain
  - Client has not seen a reply
    - Reply was lost - OR - request never executed
  - Resend phase:
    - MDS reconstructs replies (using MDS disk data for client)
    - MDS re-executes requests that were lost

Delicate issues - replay

- Replay gaps
  - Clients offer transaction sequence to servers during replay
  - There can be gaps in the sequence, for two reasons
    - Clients are missing and fail to offer transactions - BAD
    - The gaps are cases where replies are missing – BENIGN
  - 100% correct replay requires all clients to join
    - During restart the server waits for clients to join
- Why acknowledge replies?
  - Client A creates dir D - MDS sends A fid(D)
  - Client B creates file F in fid(D)
    - So client B can only replay if fid(D) will be re-created
  - Lustre 1.8 will get past this problem
    - Clients will generate fids

Delicate issues - replay2

- Re-opening files
  - Opening “foo” requires permissions
  - After the open permissions can change
  - During re-opening in recovery must “force” re-open to work
    - This is an open bug in Lustre
    - There is not even a test that shows that it fails
      - open(“foo”); chmod(“foo”, 0)
- Open, unlinked files
  - On a normal FS both the application and the FS crash
    - Nothing to recover
  - In a cluster FS if the server crashes
    - The client will want to re-open the open unlinked file
    - Open unlinked files must be retained in ORPHAN directory

Version recovery

- Clients want to revalidate their caches
  - Always, even after disconnection
  - Answer: introduce a version of files
    - Any update, except atime updates change the version
  - Even after long disconnections clients can verify the cache
- Version based recovery
  - Allow much later, out of order replay
  - Provided the versions have not changed
  - Key to re-integration with disconnections
  - Under development at the moment
- Version based recovery can lead to incomplete replay
  - But with “commit on share” we regain correctness

Recovery Refinements - commits

- Nothing to replay
  - Any failure combination is possible (many clients & servers)
  - Nothing to replay - commit everything
- Commit everything
  - Is very slow
  - Hurts single client performance
  - With more WB caching in the client this may be OK
- Commit on share
  - Before sharing data - commit it
  - Now single client performance is good
  - Short of unlikely races any failure can be handled

Delicate issues - resending

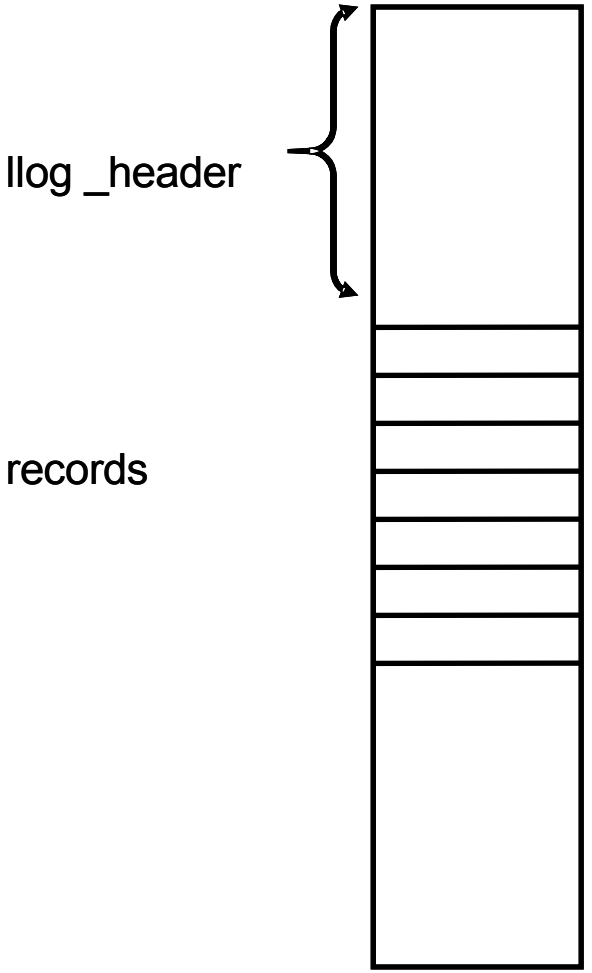
- Resending - this means no reply received
- Transaction may have executed – or not
  - The xid is re-sent by the client, last executed xid is known
  - Stored in per client export information in last_rcvd file
    - No server crash: The last executed xid
    - After server crash: The xid of the last committed request
- If the transaction executed
  - MDS performs reply reconstruction
    - Currently this uses reply data stored on disk
  - Re-doing the transaction doesn't cut it
    - E.g., how to recover previous failure or success for open("foo" , O_CREAT | O_EXCL)

llog recovery

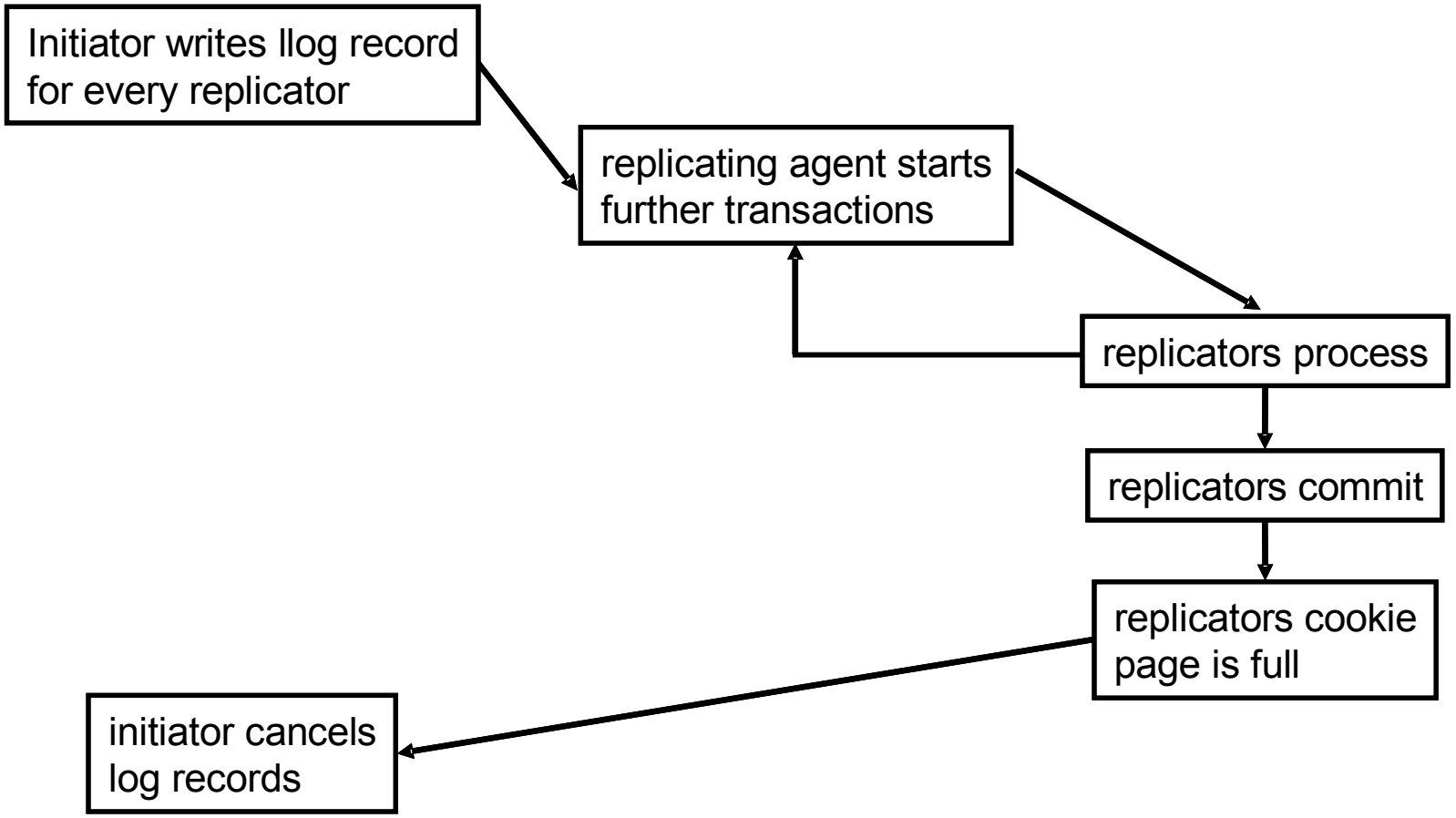
- For distributed transaction commits
  - Unlinking a file and destroying its objects
  - Updating the file size on the OSTs and on the MDT
- Terminology
  - Initiator – where the transaction is started
  - Replicators – other nodes participating
- Normal operation
  - Write a replay record for each replicator on the initiator
  - Cancel that record after the replicators commit, in bulk
- Recovery
  - Process the log entries on the initiator

llog disk structure

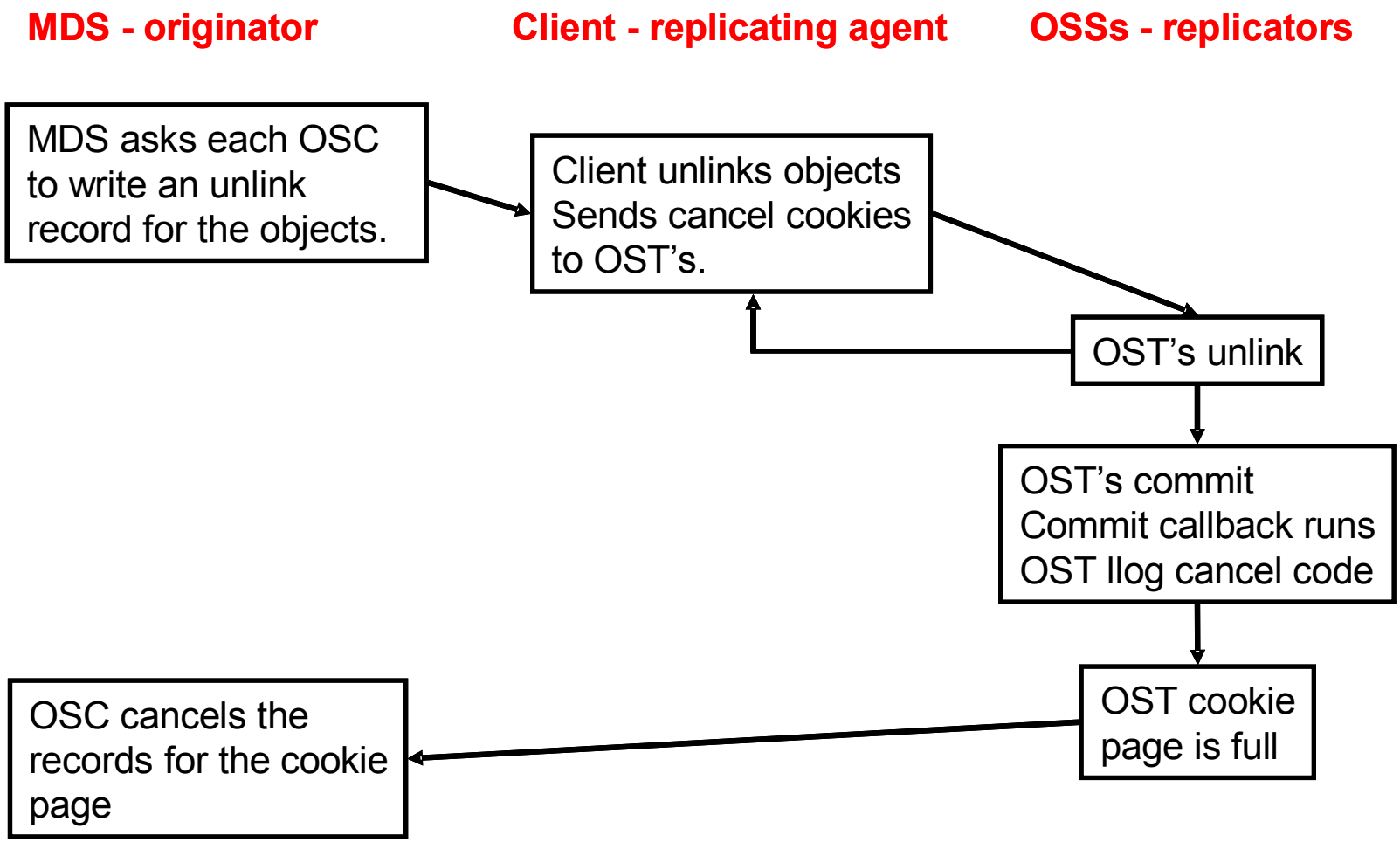
- llogs are append only logs
- 8K header, mostly bits
  - 64K records, typical size: some MB's
- llog_add
  - set bit, write record, within trans
  - writes 2-3 blocks
  - But usually coalesce in a transction
- llog_cancel
  - Clear the bit
- When all bits cleared
  - Remove the llog file
  - Many cancellations – one block



replicated transaction execution



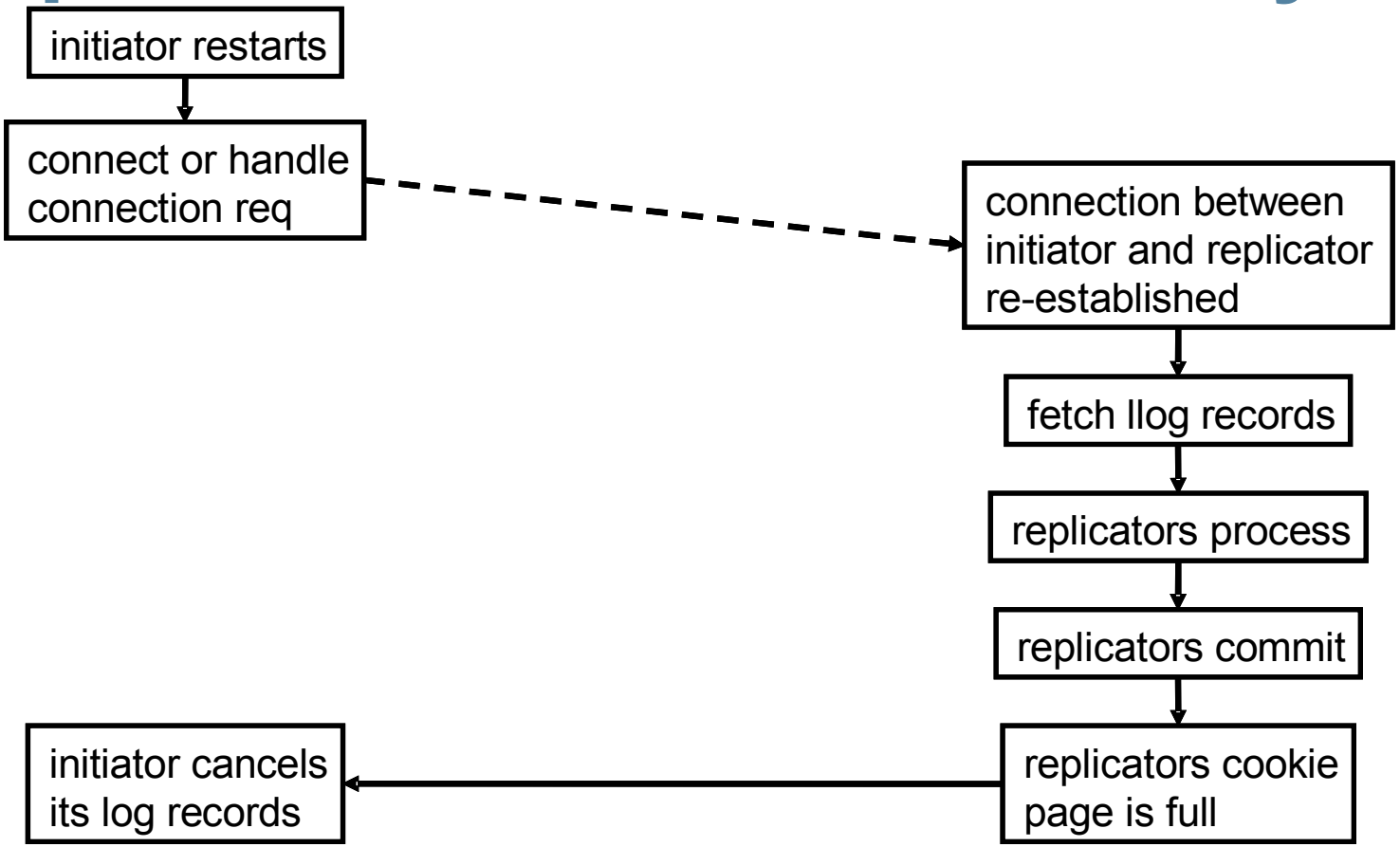
File and Object Removal - example



llog – a complex API

- Have a context
- The context has methods, often overloaded:
  - Originator cancel method cancels disk records
  - Replicator cancel method sends cookies to the originator
    - This is done during a commit callback on the replicator
    - The originator cancels the records on disk upon receipt
- An initiator context has a storage context (disk)
- An initiator needs a connection with a replicator
  - Unlink recovery- the OSC's on the MDT are the originator
    - Other arrangements would expose striping info to the MDS
  - The OSC's storage context is on the MDT

Replicated transaction recovery



E.g. - initiator is MDS with unlink llog records for file inodes

E.g. – replicators are OSS's with objects that were not yet removed, but should have been

OST & MDT disk layout

MDT disk file system layout

- ROOT/
  - This is the real namespace, with only Lustre files
- PENDING/
  - Holds unlinked files which are still open somewhere in the cluster
- LOGS/
  - Hold config and MDS/OSS recovery logs
- OBJECTS/
- last_rcvd
  - Header contains the last transaction number for the entire MDS
  - Also contains one entry per client, includes a UUID, last transaction number for this client, last XID, and reply-reconstruction data
- lov_objids
  - For each OST, one 64-bit object number -- the last objid that was allocated to a created file

OST disk file system layout

- O/
  - Contains objects laid out in object groups
  - Each group has a 32-directory hash
    - d0/ through d31/
  - Each group also contains a LAST_ID file (last objid given to MDS)
  - b1_4 uses:
    - Group 0 for “real” objects
    - Group 1 for echo_server objs
    - Group 2 for recovery objects
  - CMD and writeback MD cache also use groups
    - Each CMD server and each client with a WB cache gets a group
- Example real file system object #328:
  - O/0/d8/328
- Example echo-server object #328:
  - O/1/d8/328

OST disk file system layout (ctd)

- last_rcvd file
  - Contains a “UUID” (which is not really a UUID but should be)
  - Contains last transno for this OST
  - Contains per-client UUID, transno, last XID
  - Has no reply-reconstruction info on OST
    - Write is synchronous; read and destroy are idempotent
- CATALOGS/
  - Contains llogs of llogs
  - Each llog gets an entry in a catalog

THANK YOU