Asynchronous Directory Operations in CephFS

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WHO ARE THESE GUYS?

● Jeff
  ○ longtime kernel dev for RH, focusing on network filesystems (NFS and CIFS, mostly)
  ○ has done some recent work with userland ceph
  ○ recently took over upstream maintainership of kcephfs

● Patrick
  ○ Joined RH in 2016; CephFS team lead
  ○ Works on all aspects of CephFS but mostly shepherds projects now.
NETFS DIRECTORY OPERATIONS ARE SLOW

- open(..., O_CREAT), unlink(), etc.
- usually involve a synchronous round trip to server
- Affects many common workloads:
  - untar’ing files
  - rsync
  - removing directories recursively
  - compiling software
Observation: why are local file systems so fast?

- Obvious: no roundtrip latency with a remote file server.
- Local file systems **buffer metadata mutations in memory** until fsync on the directory/file or sufficient time has elapsed. Consequences:
  - Mutations can be written in batch to the journal in more efficient writes.
  - Operations are not guaranteed to be durable if no fsync is called:
    - rename, unlink, create require fsync on the containing directory file descriptor!
    - chmod, chown, setxattr require fsync on inode’s file descriptor!
Observation: why are local file systems so fast?

- Obvious: no roundtrip latency with a remote file server.
- Some (non-journaled) local file systems buffer metadata mutations in memory until fsync on the directory/file or sufficient time has elapsed. Consequences:
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  - Operations are not guaranteed to be durable if no fsync is called:
    - rename, unlink, create require fsync on the containing directory file descriptor!
    - chmod, chown, setxattr require fsync on inode’s file descriptor!
What’s CephFS?
Client

Active MDS

Standby MDS

Active MDS

Metadata Pool

Metadata Exchange

Journal Flush

Metadata Mutation

open
mkdir
listdir

read
write

Data Pool

RADOS

Client

Active MDS

Standby MDS

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open
mkdir
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Data Pool

RADOS
**CEPHFS CAPABILITIES**

- CephFS capabilities (aka caps) delegate parts of inode metadata to client
- Types: PIN, AUTH, FILE, LINK, XATTR
- All have a SHARED/EXCLUSIVE variety
- FILE caps have other bits (READ, WRITE, CACHE, BUFFER, LAZYIO)
- Shorthand notation: `pAsxLsxFsxrwcbIXsx`

```
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
| p | _ |As   x |Ls   x |Xs   x |Fs   x   c   r   w   b   a   l |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```
EXTENDING DIRECTORY CAPABILITIES

- FILE caps are largely unused on directories, except (Ds)
- Start handing them out on directories, and just interpret them differently
- So far:
  - CREATE requires Dc (aka Fc)
  - UNLINK requires Du (aka Fr)
- Work in conjunction with Fx caps
- Internally in MDS, done via a new lock caching facility
- Only handed out in response to first create or unlink in a directory
  - First call must be synchronous to establish the lock cache

```
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
| p | _ |As   x |Ls   x |Xs   x |Ds   x   c   u                 |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```
CEPHFS DIRENT CACHING

- Async dirops require reliable cached information about dentry

- Two mechanisms
  - individual positive or negative dentry lease
  - Fs caps on directory

- For latter, also track directory “completeness”
  - Basically whether we have a record of all dentries in a directory
  - Allows us to satisfy negative lookups w/o talking to the MDS
Asynchronous Metadata Mutations
SYNCHRONOUS UNLINKS (STATUS QUO)

- In CephFS, unlink is done synchronously by the client. The application does not return from the syscall until the unlink is durable.
- This is particularly slow for recursive unlinks...
unlink("dir/<1>")...
= 0

open()
= fd

getdents(fd)
= 803

unlink("dir/<1>")...
= 0

rmdir("/dir")
= 0
SHOULD WE WAIT TO TRANSMIT ASYNC REQ’S?

- Namespace ops are fundamentally different from data writeback
  
- Normal Files:
  - Data is stored in kernel’s pagecache and later written to backing store
  - High probability that recently modified data will be changed again in future
  - Advantageous to delay write requests for a bit to allow writes to be batched

- Directories:
  - Workloads that rapidly create/unlink same dentry are fairly rare
  - Not much advantage to delaying transmission of any async request (exception: rsync)
  - Might change if we deem batched calls to be useful in future
ASYNCHRONOUS UNLINK

- Requirements:
  - Fx and Du (aka Fr) caps on parent directory
  - Known positive dentry
    - Positive dentry lease
    - Fs on the directory and a positive dentry
- Fire off UNLINK call to MDS and then immediately delete the dentry locally
- When reply comes in, do only minimal processing
- rmdir() of parent has to wait for all child unlink replies to come back
  - Future work: support async rmdir!
N x (unlink /dir/...) = 0
N x (= 0)
rmdir("/dir")
= 0
readdir(f) = 803
readdir() = fd
getattr /dir
caps /dir/... Fwx
unlink /dir/
rmdir /dir
UNLINK PERFORMANCE

Where the test-dirops directory has 10k files:

$ time rm -f /mnt/cephfs/test-dirops/*

Without async dirops:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>real</td>
<td>0m10.371s</td>
<td></td>
</tr>
<tr>
<td>user</td>
<td>0m0.138s</td>
<td></td>
</tr>
<tr>
<td>sys</td>
<td>0m0.672s</td>
<td></td>
</tr>
</tbody>
</table>

With async dirops:

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<tr>
<td>real</td>
<td>0m0.385s</td>
<td></td>
</tr>
<tr>
<td>user</td>
<td>0m0.110s</td>
<td></td>
</tr>
<tr>
<td>sys</td>
<td>0m0.077s</td>
<td></td>
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</table>
TIME SPENT IN ceph_unlink()

Without async dirops:

<table>
<thead>
<tr>
<th>@unlink[rm]:</th>
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<tbody>
<tr>
<td>[512K, 1M)</td>
</tr>
<tr>
<td>[1M, 2M)</td>
</tr>
<tr>
<td>[2M, 4M)</td>
</tr>
<tr>
<td>[4M, 8M)</td>
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<tr>
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</tr>
<tr>
<td>[16M, 32M)</td>
</tr>
<tr>
<td>[32M, 64M)</td>
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With async dirops:

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<td>[16K, 32K)</td>
</tr>
<tr>
<td>[32K, 64K)</td>
</tr>
<tr>
<td>[64K, 128K)</td>
</tr>
<tr>
<td>[128K, 256K)</td>
</tr>
<tr>
<td>[256K, 512K)</td>
</tr>
<tr>
<td>[512K, 1M)</td>
</tr>
<tr>
<td>[1M, 2M)</td>
</tr>
<tr>
<td>[2M, 4M)</td>
</tr>
<tr>
<td>[4M, 8M)</td>
</tr>
<tr>
<td>[8M, 16M)</td>
</tr>
</tbody>
</table>
OPPORTUNITIES TO IMPROVE UNLINK

- **Asynchronous rmdir**
  - rmdir acts as an implicit fsync, preventing continuation until all child dirents are unlinked
  - `rm -rf /mnt/cephfs/test-dirops/` behaves differently!

- **Tuning in-flight asynchronous unlink operations**
  - Find the proper balance between slowing down the application and performing the unlinks as fast as possible. Too many operations in flight may disrupt other applications or other CephFS clients!

- **Batching unlink operations**
  - Gather up unlink operations into single RPC so MDS can more efficiently acquire locks and write journal segments.
ASYNCHRONOUS CREATE

● Requirements:
  ○ Fx and Dc (aka Fc) caps on parent directory
  ○ Known negative dentry
    ■ Negative dentry lease
    ■ Fs on parent directory + completeness
  ○ File layout (copied from first sync create in a directory)
  ○ Delegated inode number

● Fire off the create call immediately set up new inode and return from open()
● Assume newly-created inode gets full caps from MDS (pAsxLsxFsxcbrwXxs)
● Always set O_EXCL in the call to MDS
INODE NUMBER DELEGATION

- Need to know in advance what the inode number will be
  - to hash inode properly in kernel
  - allow for writes before reply comes back: solves fsync races
- MDS will now hand out ranges of inode numbers in CREATE responses
- new userland tunable: `mds_client_delegate_inos_pct`
  - “percentage of preallocated inos to delegate to client”
  - default == 50, so client usually has ~500 at a time
- Tied to MDS session
  - if session is reconnected, then (WIP) client should resend async creates with previously delegated inodes
CREATE PERFORMANCE

Create 10k files in a directory:

```bash
time for i in `seq 1 10000`; do
echo "foobaz" > $TESTDIR/$i
done
```

Without async dirops:

- real: 0m11.390s
- user: 0m0.315s
- sys: 0m0.974s

With async dirops:

- real: 0m5.519s
- user: 0m0.132s
- sys: 0m0.496s
### TIME SPENT IN ceph_atomic_open()

**Without async dirops:**

<table>
<thead>
<tr>
<th>@open[test-async-diro]:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[256K, 512K)</td>
<td>8</td>
</tr>
<tr>
<td>[512K, 1M)</td>
<td>9791</td>
</tr>
<tr>
<td>[1M, 2M)</td>
<td>187</td>
</tr>
<tr>
<td>[2M, 4M)</td>
<td>2</td>
</tr>
<tr>
<td>[4M, 8M)</td>
<td>0</td>
</tr>
<tr>
<td>[8M, 16M)</td>
<td>0</td>
</tr>
<tr>
<td>[16M, 32M)</td>
<td>0</td>
</tr>
<tr>
<td>[32M, 64M)</td>
<td>1</td>
</tr>
<tr>
<td>[64M, 128M]</td>
<td>9</td>
</tr>
<tr>
<td>[128M, 256M)</td>
<td>2</td>
</tr>
</tbody>
</table>

**With async dirops:**

| [8K, 16K)                      | 641   |
| [16K, 32K)                      | 2388  |
| [32K, 64K)                      | 6290  |
| [64K, 128K)                     | 599   |
| [128K, 256K)                    | 52    |
| [256K, 512K)                    | 1     |
| [512K, 1M)                      | 0     |
| [1M, 2M)                        | 6     |
| [2M, 4M)                        | 3     |
| [4M, 8M)                        | 0     |
| [8M, 16M)                       | 0     |
| [16M, 32M)                      | 0     |
| [32M, 64M)                      | 0     |
| [64M, 128M]                     | 0     |
| [128M, 256M)                    | 14    |
| [256M, 512M)                    | 6     |
Kernel Build (time make -j16 ; time make clean)

#!/bin/bash
mkdir linux
cd linux/
tar xf ../linux.tar
make defconfig
make -j16

Without async dirops:

<p>| | |</p>
<table>
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<tbody>
<tr>
<td>real</td>
<td>4m57.678s</td>
</tr>
<tr>
<td>user</td>
<td>26m43.167s</td>
</tr>
<tr>
<td>sys</td>
<td>4m21.124s</td>
</tr>
</tbody>
</table>

With async dirops:

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<tr>
<td>real</td>
<td>4m6.937s</td>
</tr>
<tr>
<td>user</td>
<td>25m47.064s</td>
</tr>
<tr>
<td>sys</td>
<td>3m58.909s</td>
</tr>
</tbody>
</table>
OPPORTUNITIES TO IMPROVE CREATE

- Optimize for rsync
  - In-place renames
- Batching creates similar to unlink
- Other operations: mkdir, symlink, in-place rename
- Error handling...
ERROR HANDLING

- If we return early from unlink() or open(), then what to do when the ops fail?
  - For creates, we may have already closed the file by the time reply comes in
  - Which failures are permitted by the protocol?

- From fsync(2) manpage:

  Calling fsync() does not necessarily ensure that the entry in the directory containing the file has also reached disk. For that, an explicit fsync() on a file descriptor for the directory is also needed.

- Nobody really does this, and most modern local fs’ journal the create
ERROR HANDLING (CONT’D)

● Currently after failed unlink
  ○ mark directory non-complete
  ○ invalidate dentry
  ○ set writeback error on parent directory to show up on fsync(dirfd)

● After failed create
  ○ invalidate dentry
  ○ set writeback error on parent directory
  ○ set writeback error on created inode

● One idea: propagate errors to parent directories all the way up to the root of the mount
● We may need to consider new interfaces
Questions?

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https://ceph.io/
https://github.com/ceph/ceph.git/