Asynchronous Directory Operations in CephFS

Jeff Layton <jlayton@redhat.com>
Patrick Donnelly <pdonnell@redhat.com>

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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.

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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

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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!

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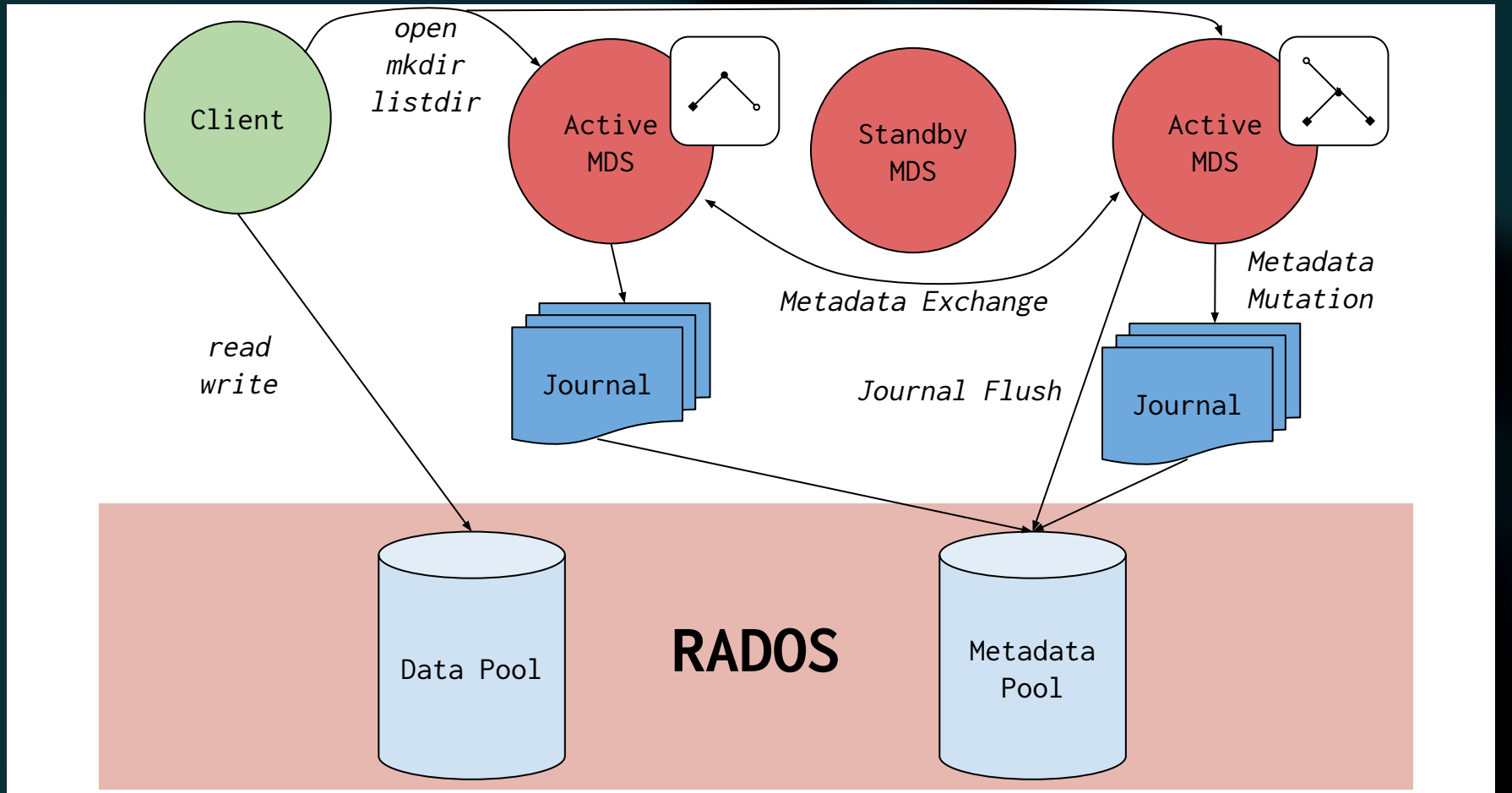
What is CephFS?


Client
open
mkdir
listdir
Active
MDS
Standby
MDS
Active
MDS
Metadata
Mutation
Metadata Exchange
read
write
Journal
Journal Flush
Journal
Data Pool
RADOS
Metadata
Pool

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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: **pAsxLsxFsxrwcbalXsx**

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

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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                   |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
```

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CEPHFS DENTRY 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

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Asynchronous Metadata Mutations

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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...

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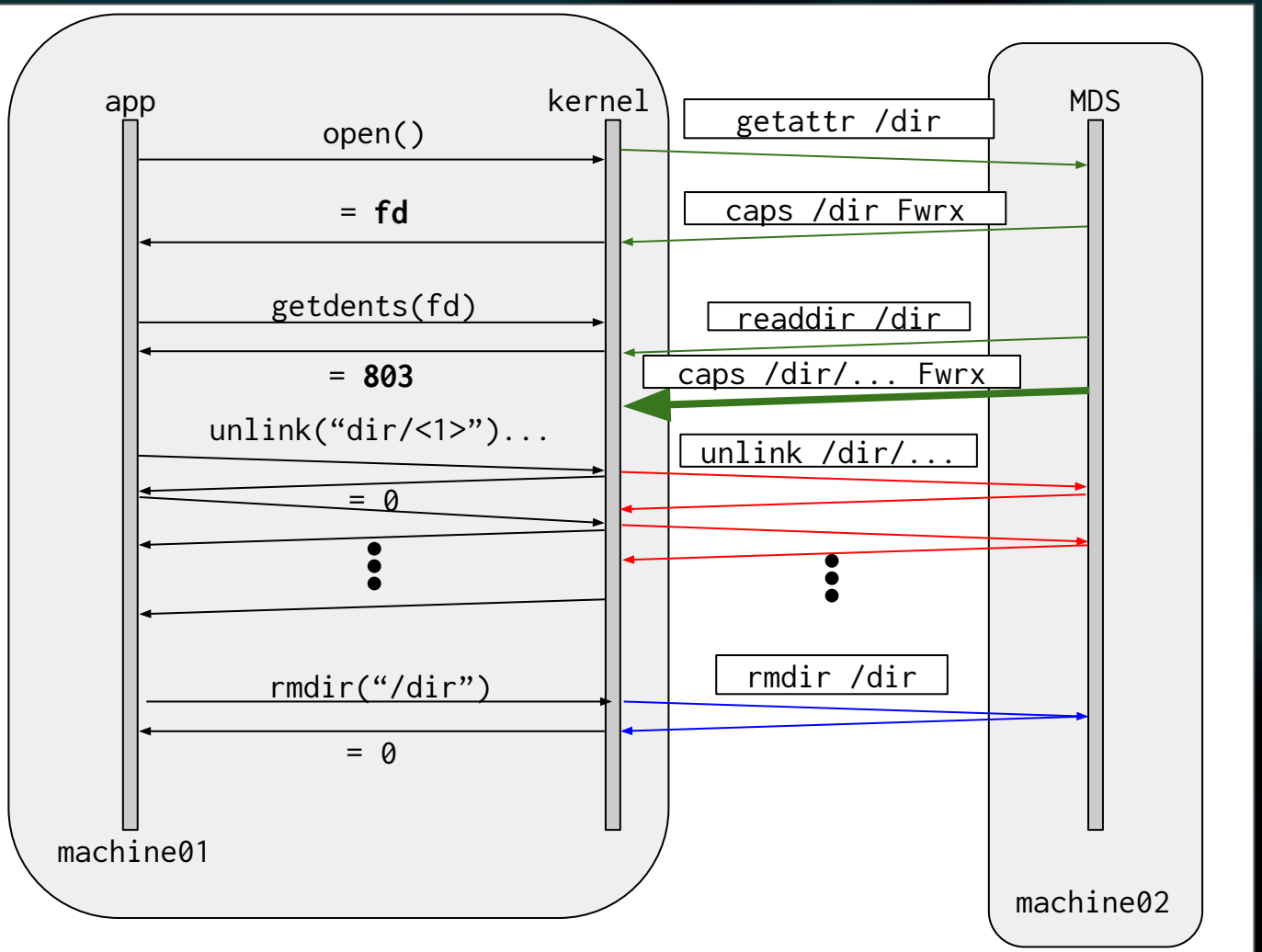
app
kernel
MDS
open()
= fd
getdents(fd)
= 803
unlink("dir/<1>")...
= 0
rmdir("/dir")
= 0
getattr /dir
caps /dir Fwrx
readdir /dir
caps /dir/... Fwrx
unlink /dir/...
rmdir /dir
machine01
machine02

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

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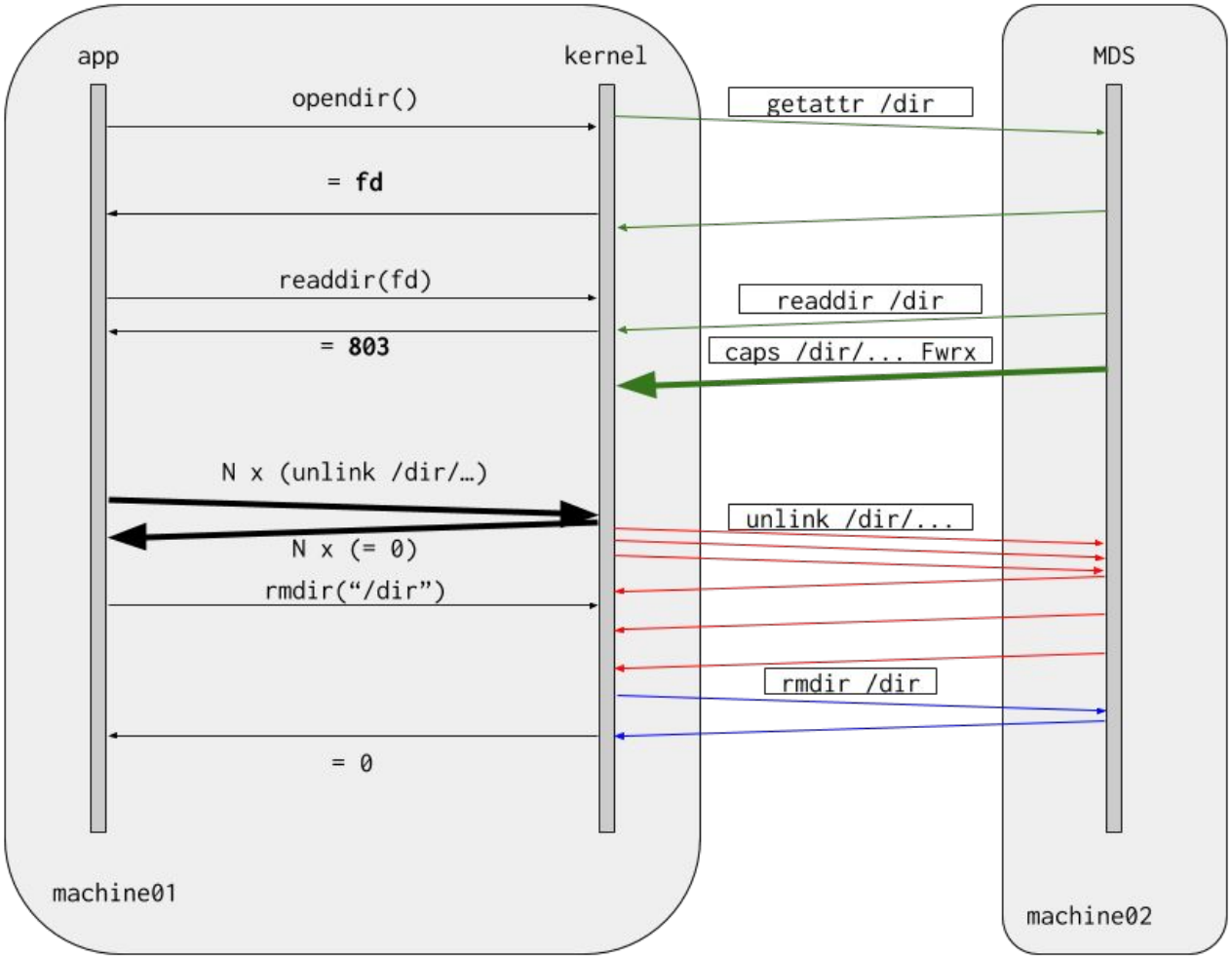
ASYNCHRONOUS UNLINK

- Requirements:
  - Dx and Du (aka Fr) caps on parent directory
  - Known positive dentry
    - Positive dentry lease
    - Dx on the directory and a positive dentry
    - Primary dentry (hardlinked files do not apply)
- Fire off UNLINK call to MDS and then immediately delete the dentry locally
- When reply comes in, do only minimal processing (mostly error handling)
- rmdir() of parent has to wait for all child unlink replies to come back
  - Future work: support async rmdir!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kernel
MDS
opendir()
= fd
readdir(fd)
= 803
N x (unlink /dir/…)
N x (= 0)
rmdir("/dir")
= 0
getattr /dir
readdir /dir
caps /dir/... Fwrx
unlink /dir/...
rmdir /dir
machine01
machine02

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UNLINK PERFORMANCE

Where the test-dirops directory has 10k files:

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

Without async dirops:

```
real    0m10.371s
user    0m0.138s
sys     0m0.672s
```

With async dirops:

```
real    0m0.385s
user    0m0.110s
sys     0m0.077s
```

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TIME SPENT IN ceph_unlink() (IN NS)

Without async dirops:

```
@unlink[rm]:
[512K, 1M)          7855
[1M, 2M)            2033
[2M, 4M)              92
[4M, 8M)               5
[8M, 16M)              5
[16M, 32M)             2
[32M, 64M)             8
```

With async dirops:

```
@unlink[rm]:
[1K, 2K)            3380
[2K, 4K)            3348
[4K, 8K)            3182
[8K, 16K)             65
[16K, 32K)            19
[32K, 64K)             0
[64K, 128K)            0
[128K, 256K)           1
[256K, 512K)           1
[512K, 1M)             1
[1M, 2M)               1
[2M, 4M)               1
[4M, 8M)               0
[8M, 16M)              1
```

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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.

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ASYNCHRONOUS CREATE

- Requirements:
  - Dx and Dc (aka Fc) caps on parent directory
  - Known negative dentry
    - Negative dentry lease
    - Ds 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 OPEN reply comes back
- 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

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CREATE PERFORMANCE

Create 10k files in a directory:

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

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TIME SPENT IN ceph_atomic_open() (IN NS)

Without async dirops:

```
@open[test-async-diro]:
[256K, 512K)               8
[512K, 1M)              9791
[1M, 2M)                 187
[2M, 4M)                   2
[4M, 8M)                   0
[8M, 16M)                  0
[16M, 32M)                 0
[32M, 64M)                 1
[64M, 128M)                9
[128M, 256M)               2
```

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
```

??

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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:

```
real    4m57.678s
user    26m43.167s
sys     4m21.124s
```

With async dirops:

```
real    4m6.937s
user    25m47.064s
sys     3m58.909s
```

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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

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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
- syncfs (patchset in progress to help enable this)
- We may need to consider new interfaces

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Questions?

Jeff Layton <jlayton@redhat.com>
Patrick Donnelly <pdonnell@redhat.com>

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

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