Ceph: A Scalable, High-Performance Distributed File System

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Outline

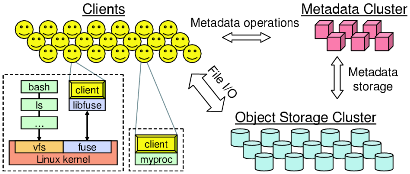
Problem

- Distributed filesystems allow aggregation of resources
  - Can increase fault-tolerance
  - Can increase performance
  - Increases complexity
- Metadata is a bottleneck in many distributed filesystems
  - Centralized metadata
  - Distributed metadata
- Can we make a distributed filesystem that scales on both data and metadata operations?

Goals of Ceph

- Achieve scalability to petabyte workloads, while maintaining
  - Performance
  - Reliability
- Scalability?
  - Storage capacity
  - Throughput
  - Scale the above while maintaining useful performance for individuals

How Does Ceph Attempt to Accomplish This?



- Decoupling data and metadata
  - A Ceph cluster consists of servers responsible for storing objects, and servers responsible for managing metadata
- *Dynamic* distributed metadata management
  - Robust against failures and workload changes
- Reliable Autonomic Distributed Object Storage
  - Leverage “intelligence” available at each node in a cluster

What are Metadata?

- Metadata are information about data
  - Length, permissions, creator, modification time, . . .
  - File name?
- Almost every filesystem access affects metadata
- Different types of metadata can have different consistency requirements

Traditional Block Storage

- In traditional block storage, one piece of metadata is the allocation list
  - Sequence of disk block ranges that comprise the data of the file
- Managing this list takes a significant amount of computrons
- In a distributed setting, disk blocks are too low-level an abstraction

Object Storage

- *Objects* consist of paired data and metadata
- An Object storage device is responsible for keeping track of where's the object's bytes are on disk
- Thus, object storage relies on intelligence at storage nodes to relieve some of the management load

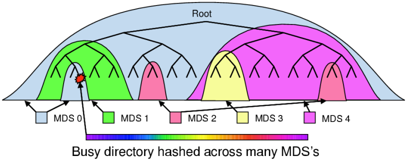
A Simple Object Storage System

- Consider a simple distributed filesystem
  - Centralized directory server: "Where is /tmp/foo?"
  - Distributed file servers: "Give me bytes 9043-43880 of /tmp/foo"
- This design does not scale:
  - Can the directory server handle 10,000 requests/second? 1,000,000?
  - Can a single file server serve up a 10 MB file to 1,000 hosts?

Metadata Distribution in Ceph

- In the past, distributed filesystems have used static sub-tree partitioning to distribute filesystem load
  - This does not perform optimally for some cases (e.g. `/tmp`, `/var/run/log`)
  - It also performs poorly when the workload changes
- To offset this lack of optimality, more recent distributed filesystems have opted to distribute metadata with a hashing function
  - This removes the performance gains from directory locality
- Ceph uses a new approach, dynamic sub-tree partitioning

Dynamic Sub-Tree Partitioning

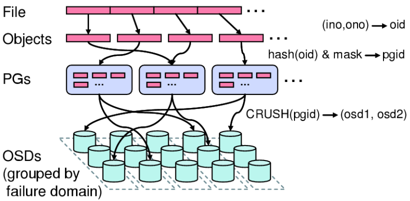


- Each MDS is responsible for some sub-tree of the filesystem hierarchy
- Whenever an operation "visits" an inode (directory or file), the MDS increments that inode's time-decay counter
- MDSs compare their counter values periodically
- When an imbalance is detected, the MDS cluster reassigns the responsiblity over some sub-trees to balance the counter values
- Extremely busy directories can be hashed across multiple MDSs

A Naïve Object Placement Method

- To find where to put a chunk of a file, $hash(inode.chunkNum) mod NumServers$
- But what happens when a server goes down or we add a server?
  - The hashing function needs a new modulus
- In a “petascale” distributed filesystem, failures and expansion must be regarded as the rule, rather than the exception
- Is there a better way to place chunks?

Distributing Objects in Ceph



- Each object is mapped to a Placement Group by a simple hash function with an adjustable bitmask
  - This bitmask controls the number of PGs
- Placement Groups (PGs) are mapped to each Object Storage Device (OSD) by a special mapping function, CRUSH
  - Number of PGs per OSD affects load balancing

CRUSH

- A special-purpose mapping function
- Given as input a PG identifier, a cluster map, and a set of placement rules, it deterministically maps each PG to a sequence of OSDs, $\vec{R}$.
- This sequence is pseudo-random but deteministic
- "With high probability", this achieves good distribution of objects and metadata
- This distribution is called "declustered"

Cluster Maps

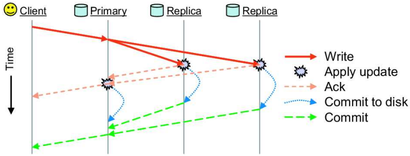
- A cluster map is composed of devices and buckets
  - **Devices** are leaf nodes
  - **Buckets** may contain devices or other buckets
- The OSDs that make up a cluster or group of clusters can be organized into a hierarchy
- This hierarchy can reflect the physical or logical layout of the cluster or network
  - Room123 (*root*)
  - Row1, Row2, . . . , Row8
  - Cabinet1, Cabinet2, . . . , Cabinet16
  - Disk1, Disk2, . . . , Disk256

Placement Rules

- Specify how the replicas of a PG should be placed on the cluster
- The following example distributes three replicas across single disks in each of three cabinets, all in the same row
- This pattern reduces or eliminates inter-row replication traffic

Action	Resulting $\vec{i}$
take(Room123)	Room123
select(1,row)	Row2
select(3,cabinet)	Cabinet4 Cabinet8 Cabinet9
select(1,disk)	Disk44 Disk509 Disk612

Safety vs. Synchronization



- When a client writes data, it sends the write to the Primary
- The Primary forwards the data to the Secondaries, who *ack* that they've received the data and it's been applied to their page caches
- When the Primary receives all the Secondary *ack*s, it returns an *ack* back to the client
- At this point, the client knows that any other client accessing the object will see a consistent view of it

Safety vs. Synchronization (continued)

- So how does Ceph treat data safety?
- Each OSD aggressively flushes its caches to secondary storage
- When the Secondaries have flushed each update, they send a *commit* message to the Primary
- After collecting all the Secondaries' *commit*s, the Primary sends a *commit* to the client
- Clients keep their updates buffered until receipt of a *commit* message from the Primary
  - (Why is this necessary?)

Commonality of Failures

- Failures must be assumed in a "petascale" filesystem consisting of hundreds or thousands of disks
- Centralized failure monitoring:
  - Places a lot of load on the network
  - Can not see "through" a network partition
- Can we distribute monitoring of failures?

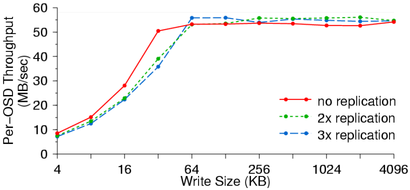
Monitors

- Monitors are processes that keep track of transient and systemic failures in the cluster
- They are responsible with providing access to a consistent cluster map
- When the monitors change the cluster map, they propagate that change to the affected OSDs
  - The updated cluster map (since it is small) propagates via other inter-OSD communication to the whole cluster
- When an OSD receives an updated map, it determines if the ownership of any of its PGs have changed
  - If so, it directly connects to the other OSD and replicates its PG there

So What If A Rack Of Servers Explodes?

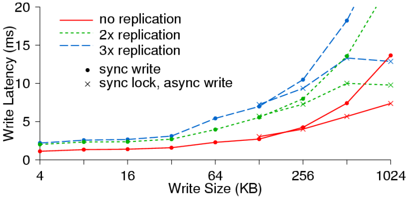
- Each OSD keeps track of the last time it heard from each other server it shares a Placement Group with (replication traffic serves as heartbeats)
- When a node goes down, it isn't heard from in a short time, and is marked *down* (but not *out*) by the monitors.
- If the node doesn't recover quickly, it is marked *out*, and another OSD joins each of the PGs that was affected in order to bring the replication level back up
- Replication of data on the down/out node is prioritized by the other OSDs

Throughput and Latency



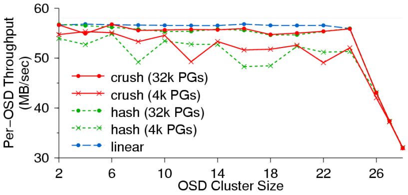
- 14-node OSD cluster
- Load is generated by 400 clients running on 20 other nodes
- Plateau indicates the physical limitation of disk throughput

Throughput and Latency (continued)



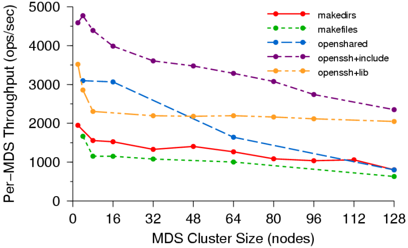
- No difference for low write sizes between two and three replicas
- At higher write sizes, network transmission times dominate network latency

Throughput and Latency (continued)



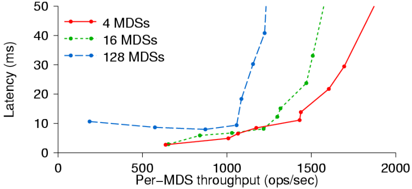
- OSD throughput scales linearly with the size of the OSD cluster until the network switch is saturated
- More PGs even load out more, giving better per-node throughput

Metadata Operation Scaling



- 430-node cluster, varying number of MDSs
- Metadata-only workloads
- Only a per-node throughput slowdown of 50% for large clusters

Metadata Operation Scaling (continued)



- From the *makedirs* workload
- Larger clusters have less-optimal metadata distributions, resulting in lower throughput
- However, this is still very much adequate and performant for a large distributed filesystem

Summary

- Ceph is a distributed filesystem that scales to extremely high loads and storage capacities
- Latency of Ceph operations scales well with the number of nodes in the cluster, the size of reads/writes, and the replication factor
- By offering slightly non-POSIX semantics, they achieve big performance wins for scientific workloads
- Distributing load with a cluster-wide mapping function (CRUSH) is both effective and performant