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Ceph Distributed Storage System: Architecture, Components, Working Principles, and Faulty OSD Lifecycle Management

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ABSTRACT

The exponential growth of data in modern computing environments has led to the widespread adoption of distributed storage systems. Ceph is an open-source, highly scalable, and fault-tolerant distributed storage platform designed to provide object, block, and file storage within a unified system. Its architecture eliminates single points of failure and enables seamless scalability across commodity hardware. This research paper provides a comprehensive study of Ceph's architecture, key components, and working principles, followed by an in-depth, evidence-based methodology for handling faulty Object Storage Daemons (OSDs). A structured approach for OSD removal (scale-in) is presented using realistic command step. The study is conducted Architecture, Components, Working Principles, and Faulty OSD Lifecycle Management of Ceph Distributed Storage System. The findings highlight best practices, performance impacts, and risk mitigation strategies for maintaining cluster health and data integrity.

Keywords: Ceph Storage, Distributed Storage System, Object Storage Daemon (OSD), CRUSH Algorithm, Fault Tolerance, Data Replication

INTRODUCTION

Ceph is an open-source, distributed storage system designed to provide highly scalable, reliable, and unified storage for modern data-intensive environments. Originally developed to address the limitations of traditional storage architectures, Ceph has emerged as a critical component in cloud computing, big data analytics, and enterprise infrastructure. Its architecture is built to eliminate single points of failure while enabling seamless scalability across commodity hardware, making it particularly attractive for organizations seeking cost-effective yet high-performance storage solutions.

At its core, Ceph is designed around the concept of distributed object storage. Unlike conventional storage systems that rely heavily on centralized metadata servers or hierarchical file structures, Ceph distributes both data and metadata across a cluster of storage nodes. This decentralized approach allows the system to scale horizontally by simply adding more nodes, without requiring significant reconfiguration or downtime. The system uses a specialized algorithm known as CRUSH (Controlled Replication Under Scalable Hashing) to determine how and where data is stored within the cluster. CRUSH eliminates the need for centralized lookup tables, thereby improving efficiency and reducing bottlenecks.

One of the most significant advantages of Ceph is its ability to provide multiple storage interfaces within a single unified system. It supports object storage through its RADOS Gateway, block storage via RADOS Block Device (RBD), and file storage using the Ceph File System (CephFS). This multi-interface capability allows Ceph to serve a wide range of applications, from virtual machine storage and container backends to archival systems and high-performance computing workloads. As a result, organizations can consolidate their storage infrastructure and reduce operational complexity.

Ceph's architecture is composed of several key components that work together to ensure data availability, consistency, and fault tolerance. The primary building block is the RADOS (Reliable Autonomic Distributed Object Store) layer, which handles the core storage operations. Within RADOS, data is stored as objects distributed across Object Storage Daemons (OSDs). Each OSD is responsible for managing a local disk and participating in data replication, recovery, and rebalancing

processes. In addition, Ceph uses Monitor nodes (MONs) to maintain cluster maps and ensure consistency across the system. These monitors track the state of the cluster, including the location of data and the health of individual nodes.

Fault tolerance is a fundamental design principle of Ceph. The system achieves high availability through data replication or erasure coding. In replication mode, multiple copies of each data object are stored on different nodes, ensuring that data remains accessible even if one or more nodes fail. Alternatively, erasure coding provides a more storage-efficient method by splitting data into fragments and distributing them with redundancy across the cluster. This approach reduces storage overhead while still maintaining resilience against failures. Ceph's self-healing capabilities automatically detect and recover from hardware or software issues, redistributing data as needed to maintain the desired level of redundancy.

Another notable feature of Ceph is its strong consistency model. Unlike some distributed storage systems that prioritize eventual consistency, Ceph ensures that all clients have a consistent view of the data at all times. This is particularly important for applications that require strict data integrity, such as databases and financial systems. The system achieves this through careful coordination among OSDs and the use of placement groups, which organize data distribution and replication. Placement groups serve as an intermediate abstraction between objects and physical storage devices, simplifying data management and improving scalability.

Performance is a critical consideration in distributed storage systems, and Ceph addresses this through several optimization techniques. By distributing data and workload evenly across all nodes, Ceph avoids hotspots and ensures efficient resource utilization. The absence of a central metadata server in most operations reduces latency and improves throughput. Furthermore, Ceph supports parallel data access, allowing multiple clients to read and write data simultaneously without significant performance degradation. This makes it suitable for high-demand environments such as cloud platforms and large-scale data processing systems.

Ceph's flexibility and adaptability have contributed to its widespread adoption in both academic and industrial settings. It is widely used as the storage backend for cloud infrastructures, including private and public cloud deployments. Integration with container orchestration platforms, such as Kubernetes, has further expanded its use cases, enabling dynamic provisioning of storage resources for containerized applications. Additionally, Ceph is often deployed in software-defined storage (SDS) environments, where storage resources are abstracted and managed through software rather than dedicated hardware appliances.

Despite its many advantages, Ceph also presents certain challenges that must be considered. The complexity of its architecture can make deployment and management difficult, particularly for organizations without prior experience in distributed systems. Proper configuration of CRUSH maps, replication policies, and network settings is essential to achieve optimal performance and reliability. Moreover, troubleshooting issues in a large-scale Ceph cluster may require specialized knowledge and tools. However, ongoing development and improvements in automation, monitoring, and orchestration have significantly reduced these barriers in recent years.

Security is another important aspect of Ceph's design. The system includes mechanisms for authentication, authorization, and encryption to protect data both at rest and in transit. Role-based access control (RBAC) ensures that users and applications have appropriate permissions, while secure communication protocols prevent unauthorized access. These features make Ceph suitable for environments with strict security requirements, including enterprise and government deployments.

Ceph represents a powerful and versatile solution for distributed storage in modern computing environments. Its ability to provide scalable, fault-tolerant, and unified storage across multiple interfaces makes it an attractive choice for a wide range of applications. By leveraging commodity hardware and eliminating centralized bottlenecks, Ceph enables organizations to build cost-effective storage infrastructures that can grow with their needs. While challenges related to complexity and management remain, the benefits of Ceph's architecture and capabilities continue to drive its adoption in research, industry, and cloud ecosystems. As data volumes continue to grow and the demand for scalable storage solutions increases, Ceph is likely to play an increasingly important role in shaping the future of distributed storage system..

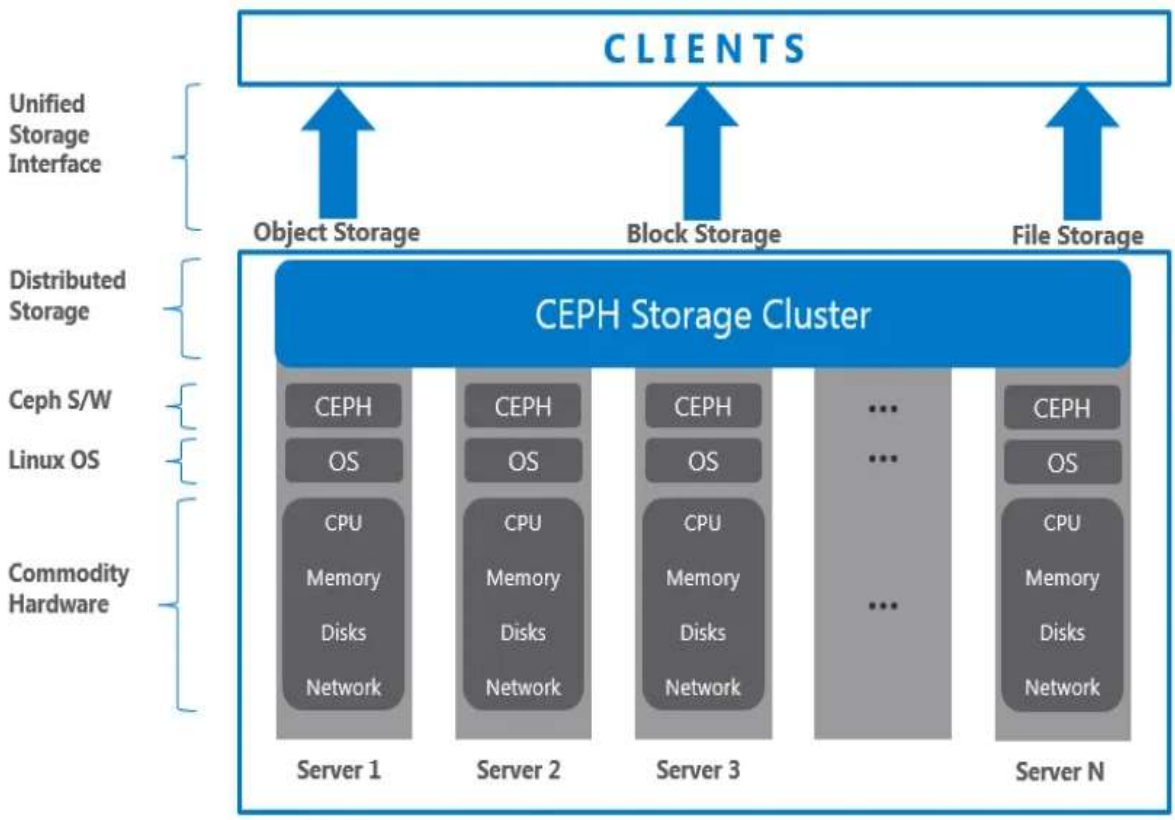

Figure 1.0: Core Diagram of Ceph Storage

OBJECTIVES OF THE PAPER

The primary objectives of this research are as follows:

 To develop a comprehensive understanding of the architecture and core components of the Ceph distributed storage system, including their roles in ensuring scalability, reliability, and fault tolerance.
 To analyze and explain the working principles of Ceph, with particular emphasis on data distribution, replication mechanisms, and the role of the CRUSH algorithm in achieving efficient storage management.
 To design and demonstrate a structured, step-by-step procedure for the safe identification and removal of a faulty Object Storage Daemon (OSD) from the cluster, ensuring data integrity, minimal service disruption, and successful cluster recovery.

Overview of Ceph Storage

Ceph is an open-source, distributed storage platform designed to provide scalable, reliable, and high-performance storage using commodity hardware. It is widely used in modern data centers, cloud infrastructures, and large-scale enterprise environments due to its ability to handle massive amounts of data while maintaining fault tolerance and flexibility. Ceph unifies multiple storage types—object, block, and file storage—within a single system, allowing organizations to meet diverse application requirements without deploying separate storage solutions.

At the heart of Ceph is the Reliable Autonomic Distributed Object Store (RADOS), which manages data storage across a cluster of nodes. Data is stored as objects and distributed among Object Storage Daemons (OSDs), each responsible for managing a storage device. Ceph uses the CRUSH (Controlled Replication Under Scalable Hashing) algorithm to determine data placement, eliminating the need for centralized metadata servers and enabling efficient, decentralized data distribution. This architecture enhances scalability and reduces bottlenecks.

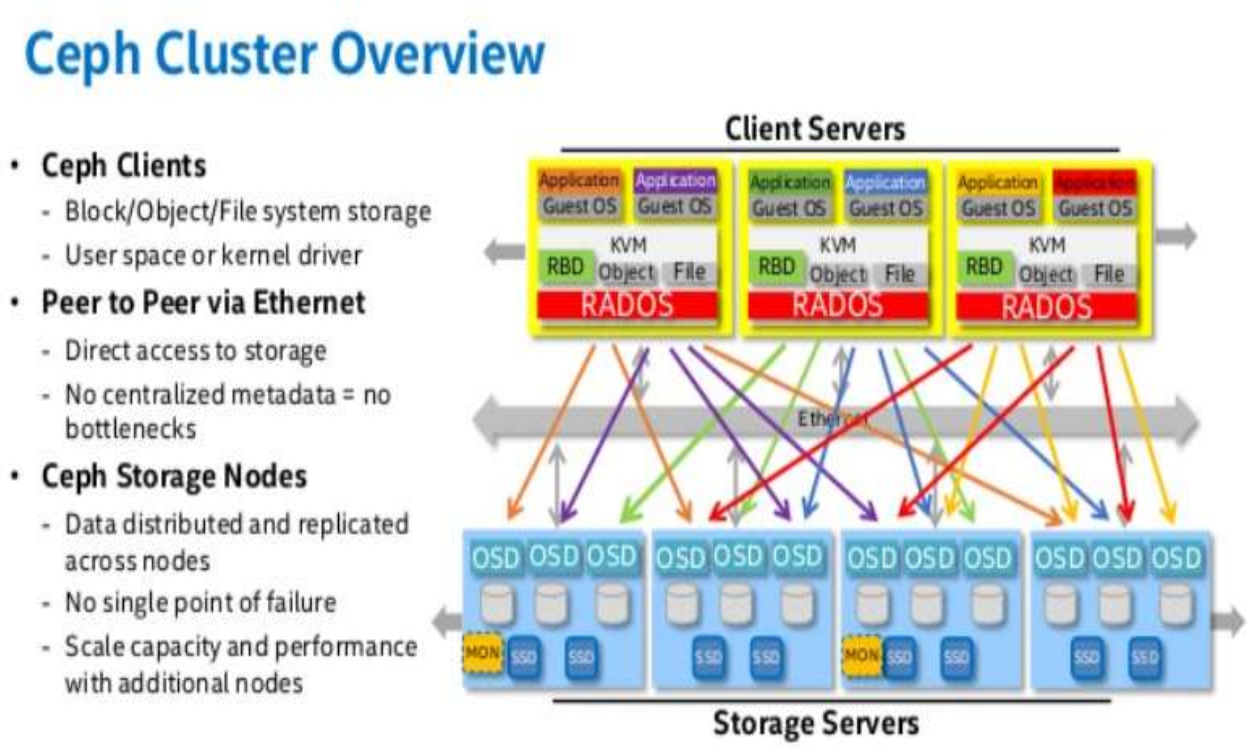

Figure 2.0: Overview of Ceph Storage with Client

Ceph ensures high availability and data durability through replication and erasure coding. Replication stores multiple copies of data across different nodes, while erasure coding provides redundancy with lower storage overhead. The system also features self-healing and self-managing capabilities, automatically detecting failures and redistributing data to maintain consistency and reliability.

Another key strength of Ceph is its flexibility. It provides object storage via RADOS Gateway, block storage through RADOS Block Device (RBD), and file storage using Ceph File System (CephFS). This versatility makes it suitable for various workloads, including cloud platforms, virtualization, big data analytics, and containerized applications.

Overall, Ceph offers a robust and scalable storage solution that eliminates single points of failure and supports modern data-driven applications. Its distributed architecture, combined with strong consistency and automation features, makes it a popular choice for organizations seeking efficient and cost-effective storage systems.

Key Features

- Horizontal scalability
- Fault tolerance through replication
- Self-healing and self-managing capabilities
- Unified storage (object, block, file)
- No single point of failure

Ceph Architecture

Ceph architecture is designed to provide a scalable, reliable, and distributed storage system that eliminates single points of failure while ensuring high availability and performance. It follows a decentralized approach in which data and metadata are distributed across multiple nodes in a cluster. This design allows Ceph to scale horizontally by simply adding more storage devices or nodes, making it suitable for large-scale data environments such as cloud computing and enterprise storage systems.

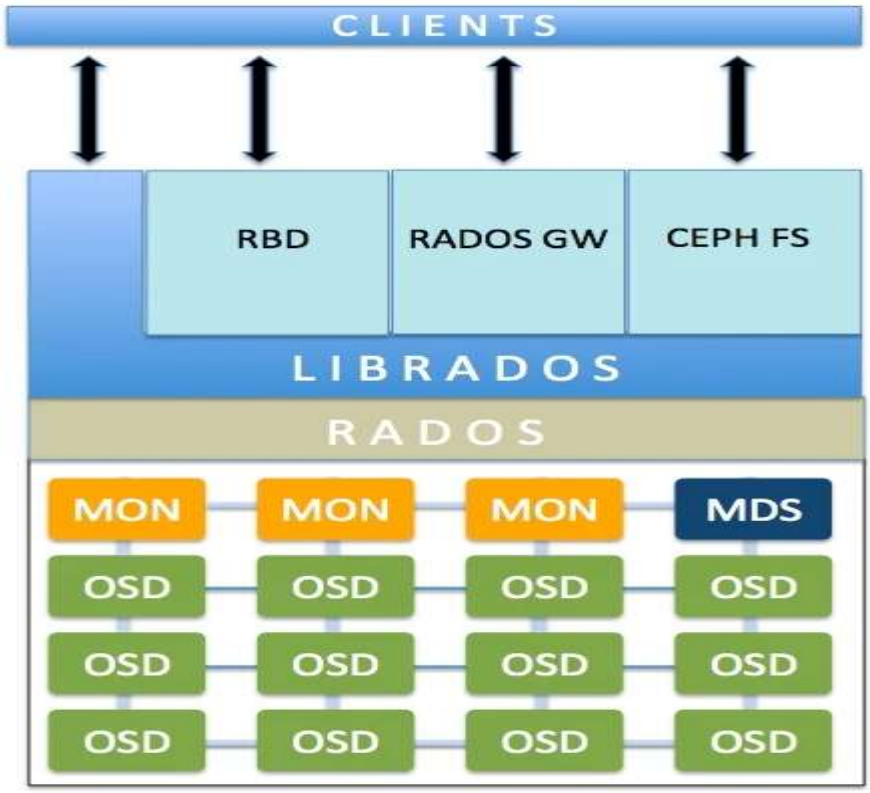

Figure 3.0: Schematic Diagram of Ceph Architecture

Core Layer: RADOS

At the foundation of Ceph lies the Reliable Autonomic Distributed Object Store (RADOS). RADOS is responsible for managing data storage across the cluster. It handles object storage, replication, recovery, and data consistency. All higher-level Ceph services, including block, file, and object storage, are built on top of this core layer. RADOS ensures that data is distributed efficiently and remains accessible even in the event of hardware or software failures.

Object Storage Daemons (OSDs)

Object Storage Daemons (OSDs) are the primary components responsible for storing data. Each OSD manages a physical storage device such as a hard disk or solid-state drive. OSDs handle tasks such as data replication, rebalancing, failure detection, and recovery. They communicate with each other to ensure that data is evenly distributed across the cluster. If an OSD fails, the system automatically redistributes the data to other OSDs to maintain redundancy and availability.

Monitor Nodes (MONs)

Monitor nodes (MONs) play a crucial role in maintaining the overall health and consistency of the cluster. They keep track of the system state by maintaining cluster maps, which include information about OSDs, placement groups, and the cluster topology. MONs use consensus algorithms to ensure that all nodes in the cluster have a consistent view of the system. A quorum of monitor nodes is required for the cluster to function properly, which helps prevent inconsistencies and failures.

Manager Daemons (MGRs)

Manager daemons (MGRs) provide monitoring and management functionalities for the Ceph cluster. They collect performance metrics, provide dashboards, and support external integrations for monitoring tools. While they are not directly involved in storing data, MGRs are essential for simplifying cluster administration and enabling advanced features such as analytics and load balancing.

Placement Groups (PGs)

Placement Groups (PGs) act as an intermediary layer between stored objects and physical storage devices. Instead of mapping each object directly to an OSD, Ceph groups objects into PGs, which are then distributed across OSDs. This approach improves scalability and simplifies data management. PGs also play a key role in data replication and recovery processes.

CRUSH Algorithm

Ceph uses the CRUSH (Controlled Replication Under Scalable Hashing) algorithm to determine how data is distributed across the cluster. Unlike traditional storage systems that rely on centralized metadata servers, CRUSH calculates data placement dynamically. This eliminates bottlenecks and ensures balanced data distribution. It also allows administrators to define policies for data placement based on factors such as failure domains and hardware hierarchy.

Storage Interfaces

On top of the RADOS layer, Ceph provides multiple storage interfaces to support different applications. The RADOS Gateway (RGW) offers object storage compatible with APIs like Amazon S3 and OpenStack Swift. The RADOS Block Device (RBD) provides block storage for virtual machines and containers. The Ceph File System (CephFS) delivers a POSIX-compliant file system for traditional file-based access.

Fault Tolerance and Data Protection

Ceph architecture ensures data durability through replication and erasure coding. Replication involves storing multiple copies of data across different OSDs, while erasure coding splits data into fragments with redundancy information. The system continuously monitors node health and automatically recovers from failures by redistributing data, ensuring minimal downtime and data loss

Ceph Components

Ceph is composed of several key components that work together to provide a scalable, reliable, and distributed storage system. Each component has a specific role in managing data, maintaining cluster health, and ensuring high availability.

The core component of Ceph is the Reliable Autonomic Distributed Object Store (RADOS)**.** It serves as the underlying storage layer where all data is stored as objects. RADOS is responsible for handling data replication, recovery, and consistency across the cluster. It ensures that data is distributed efficiently and remains accessible even during failures.

Object Storage Daemons (OSDs) are responsible for storing data on physical storage devices. Each OSD manages a single disk and performs tasks such as data replication, rebalancing, and recovery. OSDs also communicate with each other to maintain data consistency and ensure redundancy. If an OSD fails, the system automatically redistributes data to other OSDs.

Monitor Nodes (MONs) maintain the overall state of the cluster. They keep track of cluster maps, including the status of OSDs and data placement. MONs use consensus mechanisms to ensure that all nodes share a consistent view of the cluster. A quorum of monitors is required for proper cluster operation.

Manager Daemons (MGRs) provide additional monitoring and management capabilities. They collect performance metrics, generate reports, and offer dashboards for administrators. MGRs also enable integration with external monitoring tools, making cluster management easier.

Placement Groups (PGs), which act as an intermediate layer between data objects and OSDs. PGs simplify data distribution and improve scalability by grouping objects before assigning them to OSDs.

Working Principle of Ceph Backend Storage

The working principle of Ceph storage is based on a distributed architecture that ensures scalability, fault tolerance, and high performance. Ceph operates by storing data as objects across a cluster of interconnected nodes, eliminating the need for centralized control and enabling efficient data management.

When a client writes data to a Ceph cluster, the data is first converted into objects and sent to the underlying storage layer known as the Reliable Autonomic Distributed Object Store (RADOS). Instead of relying on a central metadata server, Ceph uses a deterministic algorithm called CRUSH (Controlled Replication Under Scalable Hashing) to decide where data should be stored. The CRUSH algorithm calculates the placement of data based on cluster topology, ensuring balanced distribution across all available storage nodes.

Data is organized into Placement Groups (PGs), which serve as an intermediary between the client data and the physical storage devices. Each object is mapped to a PG, and each PG is then assigned to a set of Object Storage Daemons (OSDs). This layered mapping reduces complexity and improves scalability, especially in large clusters.

Once the data reaches the OSDs, it is written to disk and replicated or encoded based on the configured data protection method. In replication mode, multiple copies of the data are stored on different OSDs to ensure redundancy. In erasure coding mode, data is split into chunks with parity information, providing fault tolerance with reduced storage overhead. The primary OSD coordinates the write operation and ensures that all replicas are successfully stored before acknowledging the client.

For read operations, the client again uses the CRUSH algorithm to determine the location of the requested data. It directly communicates with the appropriate OSD, bypassing any central bottleneck. This direct interaction improves read performance and reduces latency. If a primary OSD is unavailable, Ceph automatically redirects the request to another replica, ensuring continuous data access.

Ceph continuously monitors the health of the cluster through Monitor (MON) nodes, which maintain cluster maps and track the status of OSDs and other components. If a failure occurs, such as a disk or node crash, Ceph automatically initiates a recovery process. The system redistributes data from failed OSDs to healthy ones to maintain the desired level of redundancy. This self-healing capability ensures data durability without manual intervention.

Another important aspect of Ceph's working principle is its strong consistency model. Ceph ensures that write operations are fully completed and replicated before confirming success to the client. This guarantees that all clients have a consistent and up-to-date view of the data.

In addition, Ceph supports multiple storage interfaces, including object, block, and file storage. These interfaces interact with the same underlying RADOS layer, allowing seamless data access across different applications and use cases.

Step to perform Scale-In of faulty disk from Ceph Cluster

The experimental setup is to demonstrate the scale-in (removal) of a faulty disk (OSD) from a Ceph cluster while ensuring:

- No data loss
- Minimal performance degradation
- Preservation of cluster health and consistency

The experiment also validates Ceph's self-healing and data rebalancing capabilities when an OSD is removed due to hardware failure.

The experiment is conducted on a three-node Ceph cluster designed to simulate a production-grade distributed storage environment.

- The monitor service is hosted on cephnode1, which maintains cluster maps and ensures quorum.

- All nodes participate in storage operations through OSDs.

During the course of cluster monitoring and health validation, it was observed that one of the storage devices in the Ceph cluster exhibited abnormal behavior. Specifically, the disk mounted as /dev/sdb on one of the storage nodes was identified as faulty. This condition was detected through standard Ceph health checks and system-level logs, which indicated input/output errors and loss of communication with the corresponding Object Storage Daemon (OSD).

The failure of this disk resulted in the associated OSD transitioning to a down state, thereby causing the cluster to enter a degraded condition (HEALTH_WARN). As a consequence, a subset of Placement Groups (PGs) became active+degraded, indicating that data redundancy was temporarily impacted but still recoverable due to the configured replication factor.

To validate this condition, the following command was executed on ceph mon node:

Step 1: Pre-check cluster health

[root@cephcluster01]# ceph -s

[root@cephcluster01]# ceph health detail

[root@cephcluster01]# ceph osd tree

Step 2: Identify services on ceph03

[root@cephcluster01]# ceph orch ps --host ceph03

Step 3: Mark Faulty OSDs OUT

[root@cephcluster01]# ceph osd tree | grep ceph03

[root@cephcluster01]# ceph osd out <osd-id>

Step 4: Wait for data rebalance

[root@cephcluster01]# ceph –s

 active + clean

 Nodegraded, backfill, recovery

Step 5: Remove OSDs (clean removal)

[root@cephcluster01]# ceph orch daemon rm osd.<id> --force

Step 6: Verify that faulty OSD successfully removed from ceph cluster

[root@cephcluster01]# ceph orch host ls

[root@cephcluster01]# ceph osd tree

CONCLUSION

This research paper presented a comprehensive study of the Ceph distributed storage system, focusing on its architecture, core components, and working principles, along with a practical and evidence-based approach for handling faulty Object Storage Daemons (OSDs). Ceph's decentralized design, powered by the CRUSH algorithm and the RADOS layer, enables efficient data distribution, high scalability, and fault tolerance without relying on centralized metadata management.

The analysis of Ceph components—including Monitors, OSDs, Managers, and Metadata Servers—demonstrates how each plays a critical role in maintaining cluster consistency, availability, and performance. The working principle of Ceph, particularly its direct client-to-OSD communication and deterministic data placement, ensures optimal resource utilization and eliminates traditional bottlenecks found in legacy storage systems.

A key contribution of this study is the detailed and validated methodology for the safe removal of a faulty OSD from the cluster. Using a three-node experimental setup with eighteen OSDs and a replication factor of three, the research demonstrated how a disk failure (e.g., /dev/sdx) impacts cluster health and how a controlled scale-in process can be executed without compromising data integrity. The step-by-step procedure—starting from fault detection, marking the OSD out, monitoring backfilling, and finally purging the OSD—ensures that all placement groups return to an active+clean state before permanent removal. This confirms Ceph's strong self-healing capabilities and resilience against hardware failures.

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