## Understanding Hadoop, HDFS, and MapReduce

Let's break down the key concepts and mechanisms of **Hadoop**, **HDFS**, **MapReduce**, and the related components in detail with examples to provide a clear understanding.

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## 1. Hadoop and Its Versions

**Hadoop** is an open-source framework for processing and storing vast amounts of data in a distributed environment. It is designed to scale up from a single server to thousands of machines, offering high fault tolerance.

**Hadoop Versions**:

- **Hadoop 1.x**: First major version that introduced the basic MapReduce framework, HDFS, and YARN as a resource manager.
- **Hadoop 2.x**: Introduced **YARN (Yet Another Resource Negotiator)** for resource management, enabling better scalability, flexibility, and support for non-MapReduce applications.
- **Hadoop 3.x**: Improved scalability, performance, and added new features like support for GPUs, erasure coding, and improvements in HDFS, YARN, and other modules.

## 2. Hadoop Framework Structure

### HDFS (Hadoop Distributed File System)

HDFS is the distributed file system that allows Hadoop to store data across many machines. It is designed for high throughput and fault tolerance.

- **Block Size**: By default, HDFS splits large files into fixed-size blocks (128MB or 256MB), and these blocks are distributed across different nodes.
- **Replication**: Blocks are replicated for fault tolerance (default replication factor: 3).

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### MapReduce

MapReduce is a programming model used for processing and generating large datasets. It consists of two main phases:

- **Map Phase**: The input data is divided into small chunks, and a map function processes each chunk in parallel.
- **Reduce Phase**: After the map phase, the output from all the mappers is grouped, and a reduce function consolidates this data.

## 3. Key Hadoop Components

### NameNode (Master Node)

- The **NameNode** is the central server in HDFS that manages the **metadata**. It stores information about which blocks are stored on which nodes and manages the file system namespace. However, it does **not store data**.
- **Primary Function**: Ensures that file system operations like opening, closing, and renaming files are properly managed.

### DataNode (Slave Node)

- **DataNodes** are the worker nodes in HDFS. They store the actual **data** in the form of blocks on their local disks.
- **Primary Function**: Store, retrieve, and periodically send heartbeats to the NameNode to report their health and status.

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### JobTracker (Resource Manager in YARN)

- In **Hadoop 1.x**, the **JobTracker** was responsible for managing jobs and allocating resources for MapReduce jobs.
- In **Hadoop 2.x and later**, **YARN** (Yet Another Resource Negotiator) replaces the JobTracker and acts as the resource manager to handle resource allocation across multiple applications.

### TaskTracker (NodeManager in YARN)

- In **Hadoop 1.x**, **TaskTrackers** were responsible for executing individual tasks (map and reduce tasks).
- In **Hadoop 2.x and beyond**, **NodeManagers** take over the role of TaskTrackers, managing resources and ensuring the execution of tasks in the cluster.

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## 4. HDFS Workflow

1. **File Write**:
    - When a client writes a file, the file is split into blocks.
    - These blocks are stored across various **DataNodes** based on the replication factor set in HDFS.
    - The **NameNode** keeps track of which DataNodes store each block and its replicas.
2. **File Read**:
    - When a client reads a file, it contacts the **NameNode** for metadata to find where the blocks are stored.
    - It then directly contacts the **DataNodes** to fetch the blocks.

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## 5. Replication Factor and Fault Tolerance

### Replication Factor

- **Definition**: The replication factor is the number of copies of each data block that HDFS maintains across different DataNodes to ensure data availability and fault tolerance.
- **Default Value**: 3 (meaning 3 copies of each block are stored).

### Why Replication?

- **Fault Tolerance**: If one node fails, there are multiple replicas available for data recovery.
- **Data Availability**: Multiple replicas allow for quicker data retrieval as requests can be served by any DataNode holding the replica.

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**Example**:

1. **Cluster Size ($N$)**: 10 nodes
2. **Replication Factor ($R$)**: 3

Each block of data will be replicated on 3 different nodes. If one node fails, the data can still be accessed from the other 2 nodes.

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## 6. Ideal Replication Factor

**How to Choose Ideal Replication Factor**:

- The replication factor depends on the **cluster size**, **fault tolerance** requirements, and the **criticality** of the data.
- The formula is often used for choosing the replication factor based on fault tolerance:

$$R = N \times F$$

Where:

- $R$: Replication factor
- $N$: Number of nodes in the cluster
- $F$: Fault tolerance factor (the fraction of nodes that can fail)

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**Example**:

**Cluster Size**: 100 nodes
**Fault Tolerance**: 10% (i.e., 10 nodes can fail)

Ideal Replication Factor:

$$R = 100 \times 0.1 = 10$$

Thus, a replication factor of 10 would ensure data is always accessible, even if 10 nodes fail.

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## 7. Heart Signal in HDFS

The **heartbeat signal** is a mechanism used by **DataNodes** to communicate with the **NameNode**.

- **What it consists of**:
  - A **heartbeat** is a regular signal sent from a DataNode to the NameNode to indicate its health and status.
  - It contains information such as:
    - Disk usage
    - Block storage details
    - Node health status
- **Characteristics**:
  - Sent every few seconds (default: 3 seconds).
  - It's a lightweight message to ensure the NameNode knows which DataNodes are alive.
- **Importance**:
  - If the NameNode doesn't receive a heartbeat from a DataNode for a certain period (e.g., 10 minutes), it assumes the DataNode has failed.
  - This triggers replication of blocks to maintain the desired replication factor.

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## 8. Negative Scenarios in Hadoop (Failures and Recovery)

**Under-Replication**:

- **Scenario**: A DataNode fails, and the block count drops below the replication factor.
- **Example**: A block has 3 replicas (Replication Factor = 3), but after a node failure, there are only 2 replicas left.
- **Action**: The NameNode detects under-replication and directs other DataNodes to create another replica of the missing block.

**Over-Replication**:

- **Scenario**: A DataNode recovers and starts storing a block, causing the replication to exceed the desired number of replicas.
- **Action**: The NameNode detects over-replication and deletes excess replicas, ensuring the replication factor is maintained.

**Algorithm for Shortest Path**:

- When data needs to be replicated or retrieved, the **NameNode** may choose the **shortest path** or the **most quickly reachable node** based on the network topology, ensuring efficient data access.

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## Summary with Example:

Imagine you are working with a cluster of 10 nodes. Your data is split into blocks and stored across these nodes. You set a **replication factor** of 3, meaning each block has 3 copies stored on different nodes. If one node fails (e.g., Node 2), the system still has 2 copies of the block, ensuring data availability. The **heartbeat signal** keeps the system aware of which nodes are active, and if Node 2 goes offline, the system triggers replication to a new node to restore the replication factor.

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This structure ensures that Hadoop provides **fault tolerance**, **scalability**, and **reliability** while processing vast amounts of data across distributed systems.