1. What is a Cluster?

A **cluster** in the context of Hadoop refers to a collection of machines or nodes working together to process and store large volumes of data in a distributed manner. These machines, typically connected through a network, collaborate to handle tasks that would be too large or complex for a single machine.

Who Built the Cluster?

Clusters are built and maintained by system administrators or DevOps engineers, typically using cloud services like Amazon Web Services (AWS), Microsoft Azure, Google Cloud, or on-premises infrastructure. The setup involves installing and configuring the Hadoop ecosystem components (HDFS, MapReduce, YARN, etc.) on the machines that will be part of the cluster.

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2. Higher-End Clusters and Replication Factor

Higher-End Cluster Definition:

Higher-end clusters are large, robust clusters capable of processing petabytes of data. These clusters often have several nodes (thousands of nodes in large enterprises), high-speed interconnections, and advanced configurations to ensure scalability, performance, and fault tolerance.

Replication Factor:

The **Replication Factor** is the number of copies of a data block stored across the cluster. In most Hadoop clusters:

- The default replication factor is **3**. This means each block of data is stored in three different nodes for fault tolerance.
- Higher-end clusters may increase the replication factor to ensure even higher data availability and reliability, especially for critical data.

Choosing Replication Factor: The **ideal replication factor** depends on factors such as:

- The **size of the cluster**: Larger clusters often require higher replication factors to improve fault tolerance.

- **Fault tolerance requirements**: If you want the ability to tolerate the failure of more nodes, increase the replication factor.

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3. What Happens if the Master (NameNode) Fails?

Standby NameNode:

If the **NameNode** (the master node responsible for managing HDFS) fails, Hadoop has a **standby NameNode** (configured in **HA mode - High Availability mode**). This standby NameNode automatically takes over the responsibilities of the NameNode. In this scenario:

- The **standby NameNode** becomes active.
- The **HDFS** maintains a **checkpoint** of the file system metadata, which the standby NameNode can use to recover from failure.

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4. How is Data Handled in HDFS and MapReduce?

Step 1: Getting Python Files and Dividing into Blocks

1. A user submits a **Python script** (or any other file) to the Hadoop cluster.
2. **HDFS** divides the file into smaller chunks (called **blocks**) of a fixed size (usually 128MB or 256MB).

Step 2: Activity of the NameNode

- The **NameNode** manages the **metadata** of the file system. It keeps track of which **blocks** are stored on which **DataNodes** and ensures the replication factor is maintained.
- The NameNode does **not store the actual data** but stores the mapping of file names to blocks and the location of those blocks.

Step 3: Activity of the DataNode

- **DataNodes** are the worker nodes responsible for storing the actual data blocks.
- When the file is uploaded, the **NameNode** assigns blocks to **DataNodes**, and the DataNodes store the data.
- The DataNode is also responsible for sending **heartbeats** to the NameNode, informing it that the node is active and functioning.

Step 4: Activity of the JobTracker and Resource Manager

- **JobTracker** (Hadoop 1.x) or **Resource Manager** (Hadoop 2.x and later) manages the resource allocation and job scheduling.
    - The Resource Manager divides the job into smaller tasks (map and reduce tasks) and assigns them to **NodeManagers**.
- **NodeManager** takes care of task execution on each node.

Step 5: How Data Is Processed (Mapping and Reducing)

- **Map** tasks process the data in parallel. They are mapped to the **blocks** that store the data.
- Once the **map** phase completes, the **reduce** phase consolidates and processes the intermediate data.
- The **final output** of the MapReduce job is stored in HDFS, often in a new file or directory.

Block Size Considerations:

- If the file is **smaller** than the block size, the entire file is stored in one block, and only one DataNode stores it.
- If the file is **larger** than the block size, it is split into multiple blocks, and those blocks are distributed across different DataNodes.

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5. What if a Slave (DataNode) Fails?

How Hadoop Handles DataNode Failure:

If a **DataNode** fails:

- **Replication Factor**: If the replication factor is 3, and a DataNode storing one copy of a block fails, the block will still be accessible from the other two DataNodes. However, this results in **under-replication**.
- **Re-replication**: The **NameNode** detects the under-replicated block and instructs other DataNodes to replicate the missing block to maintain the replication factor.
- **Recovery**: Once the failed DataNode is back online, the system ensures the data is properly replicated across the cluster.

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6. Who Decides Where Data Goes If a Slave Fails?

- The **NameNode** decides the placement of data blocks when the file is written.
- If a **DataNode fails**, the **NameNode** ensures that the data is re-replicated and placed on another **DataNode** to restore the replication factor.
- The **NameNode** also considers **data locality** while placing blocks, ensuring that blocks are stored on nodes that are closest to where they are being processed.

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7. How MapReduce Works and Disk I/O Operations

MapReduce with Blocks:

- Each **Map task** operates on one block at a time.
- A **Map task** reads the input data from a DataNode, processes it, and produces intermediate output. The intermediate output is written to the **local disk** and passed to the **Reduce** tasks.

Disk I/O Operations:

If there are **N blocks**, the total **disk I/O operations** can be approximated as **2N** operations:

- **Read** operations: Each block must be read by the map tasks.

- **Write** operations: Intermediate data generated by the map tasks is written to the local disk.

For example, with **3 blocks**:

- **Disk I/O = 6 operations**: 3 reads (1 for each block) and 3 writes (1 for each intermediate output).

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8. Example of Read and Write Operations in HDFS

Scenario 1:

- **Read**: When reading a file, the client contacts the **NameNode** to get metadata and the block locations.
  - It then fetches the block data from the **DataNodes**.
  - If replication is 3, the client might read the data from any of the 3 replicas.
- **Write**: When writing a file, the client:
  1. Contacts the **NameNode** for metadata.
  2. The **NameNode** allocates blocks and replication for storage.
  3. The data is written to the **DataNodes**.
  4. The **NameNode** ensures the replication factor is maintained by placing the blocks across different DataNodes.

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9. Disk I/O Calculations in Hadoop

Example with 3 Blocks:

- If there are **3 blocks** in total:
  - **Disk I/O for Read**: **3 reads** (since each block is read once by the mapper).
  - **Disk I/O for Write**: **3 writes** (the map output is written to local storage).

Thus, the total **Disk I/O** = **6 operations**.

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10. MapReduce Job Flow

1. **Input Data**: The data is divided into blocks in **HDFS**.
2. **Map Phase**: Mappers work on the blocks of data. For each block, a Map task reads the data, processes it, and generates intermediate results.
3. **Shuffle and Sort**: Intermediate results are sorted and shuffled (grouped by key).
4. **Reduce Phase**: Reducers process the grouped data, perform the final aggregation, and write the result to **HDFS**.

Conclusion

In this detailed explanation, we discussed how Hadoop clusters function, the role of key components like the **NameNode**, **DataNode**, **JobTracker**, and **ResourceManager**, and how MapReduce processes data. We also covered fault tolerance in Hadoop (such as handling DataNode failure and replication), disk I/O operations, and the overall workflow.

Diagram:

Unfortunately, I cannot generate visual diagrams directly in this environment, but I can describe the flow:

1. **Client** submits a job to **JobTracker/ResourceManager**.
2. **ResourceManager** schedules tasks (Map and Reduce).
3. **Mappers** read blocks from **DataNodes**, process them, and write the intermediate results to local disks.
4. **Reducers** collect intermediate results, process them, and write final output back to **HDFS**