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The Hadoop Distributed File System

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Introduction

Hadoop provides a distributed file system and a framework for the analysis and transformation of very large data sets using the MapReduce paradigm. An important characteristic of Hadoop is the partitioning of data and computation across many (thousands) of hosts, and executing application computations in parallel close to their data. A Hadoop cluster scales computation capacity, storage capacity and IO bandwidth by simply adding commodity servers. Hadoop clusters at Yahoo! span 25 000 servers, and store 25 petabytes of application data, with the largest cluster being 3500 servers. One hundred other organizations worldwide report using Hadoop.

Hadoop is an Apache project; all components are available via the Apache open source license. Yahoo! has developed and contributed to 80% of the core of Hadoop (HDFS and MapReduce). HBase was originally developed at Powerset, now a department at Microsoft. Hive was originated and developed at Facebook. HDFS is the file system component of Hadoop. While the interface to HDFS is patterned after the UNIX file system, faithfulness to standards was sacrificed in favor of improved performance for the applications at hand. HDFS stores file system metadata and application data separately. As in other distributed file systems, like PVFS, Lustre and GFS, HDFS stores metadata on a dedicated server, called the NameNode. Application data are stored on other servers called DataNodes. All servers are fully connected and communicate with each other using TCP-based protocols. Unlike Lustre and PVFS, the DataNodes in HDFS do not use data protection mechanisms such as RAID to make the data durable. Instead, like GFS, the file content is replicated on multiple DataNodes for reliability. While ensuring data durability, this strategy has the added advantage that data transfer bandwidth is multiplied, and there are more opportunities for locating computation near the needed data. Several distributed file systems have or are exploring truly distributed implementations of the namespace. Ceph has a cluster of namespace servers (MDS) and uses a dynamic subtree partitioning algorithm in order to map the namespace tree to MDSs evenly. GFS is also evolving into a distributed namespace implementation. The new GFS will have hundreds of namespace servers (masters) with 100 million files per master. Lustre [7] has an implementation of clustered namespace on its roadmap for Lustre 2.2 release. The intent is to stripe a directory over multiple metadata servers (MDS), each of which contains a disjoint portion of the namespace. A file is assigned to a particular MDS using a hash function on the file name.

Architecture

NameNode

The HDFS namespace is a hierarchy of files and directories. Files and directories are represented on the NameNode by inodes, which record attributes like permissions, modification and access times, namespace and disk space quotas. The file content is split into large blocks (typically 128 megabytes, but user selectable file-by-file) and each block of the file is independently replicated at multiple DataNodes (typically three, but user selectable file-by-file). The NameNode maintains the namespace tree and the mapping of file blocks to DataNodes (the physical location of file data). An HDFS client wanting to read a file first contacts the NameNode for the locations of data blocks comprising the file and then reads block contents from the DataNode closest to the client. When writing data, the client requests the NameNode to nominate a suite of three DataNodes to host the block replicas. The client then writes data to the DataNodes in a pipeline fashion. The current design has a single NameNode for each cluster. The cluster can have thousands of DataNodes and tens of thousands of HDFS clients per cluster, as each DataNode may execute multiple application tasks concurrently. HDFS keeps the entire namespace in RAM. The inode data and the list of blocks belonging to each file comprise the metadata of the name system called the image. The persistent record of the image stored in the local host's native files system is called a checkpoint. The NameNode also stores the modification log of the image called the journal in the local host's native file system. For improved durability, redundant copies of the checkpoint and journal can be made at other servers. During restarts the NameNode restores the namespace by reading the namespace and replaying the journal. The locations of block replicas may change over time and are not part of the persistent checkpoint.

DataNodes

Each block replica on a DataNode is represented by two files in the local host's native file system. The first file contains the data itself and the second file is block's metadata including checksums for the block data and the block's generation stamp. The size of the data file equals the actual length of the block and does not require extra space to round it up to the nominal block size as in traditional file systems. Thus, if a block is half full it needs only half of the space of the full block on the local drive. During startup each DataNode connects to the NameNode and performs a handshake. The purpose of the handshake is to verify the namespace ID and the software version of the DataNode. If either does not match that of the NameNode the DataNode automatically shuts down. The namespace ID is assigned to the file system instance when it is formatted. The namespace ID is persistently stored on all nodes of the cluster. Nodes with a different namespace ID will not be able to join the cluster, thus preserving the integrity of the file system. The consistency of software versions is important because incompatible version may cause data corruption or loss, and on large clusters of thousands of machines it is easy to overlook nodes that did not shut down properly prior to the software upgrade or were not available during the upgrade. A DataNode that is newly initialized and without any namespace ID is permitted to join the cluster and receive the cluster's namespace ID. After the handshake the DataNode registers with the NameNode. DataNodes persistently store their unique storage IDs. The storage ID is an internal identifier of the DataNode, which makes it recognizable even if it is restarted with a different IP address or port. The storage ID is assigned to the DataNode when it registers with the NameNode for the first time and never changes after that. A DataNode identifies block replicas in its possession to the NameNode by sending a block report. A block report contains the block id, the generation stamp and the length for each block replica the server hosts. The first block report is sent immediately after the DataNode registration. Subsequent block reports are sent every hour and provide the NameNode with an up-todate view of where block replicas are located on the cluster. During normal operation DataNodes send heartbeats to the NameNode to confirm that the DataNode is operating and the block replicas it hosts are available. The default heartbeat interval is three seconds. If the NameNode does not receive a heartbeat from a

DataNode in ten minutes the NameNode considers the DataNode to be out of service and the block replicas hosted by that DataNode to be unavailable. The NameNode then schedules creation of new replicas of those blocks on other DataNodes. Heartbeats from a DataNode also carry information about total storage capacity, fraction of storage in use, and the number of data transfers currently in progress. These statistics are used for the NameNode's space allocation and load balancing decisions. The NameNode does not directly call DataNodes. It uses replies to heartbeats to send instructions to the DataNodes.

HDFS

Client User applications access the file system using the HDFS client, a code library that exports the HDFS file system interface. Similar to most conventional file systems, HDFS supports operations to read, write and delete files, and operations to create and delete directories. The user references files and directories by paths in the namespace. The user application generally does not need to know that file system metadata and storage are on different servers, or that blocks have multiple replicas. When an application reads a file, the HDFS client first asks the NameNode for the list of DataNodes that host replicas of the blocks of the file. It then contacts a DataNode directly and requests the transfer of the desired block. When a client writes, it first asks the NameNode to choose DataNodes to host replicas of the first block of the file. The client organizes a pipeline from node-to-node and sends the data. When the first block is filled, the client requests new DataNodes to be chosen to host replicas of the next block. A new pipeline is organized, and the client sends the further bytes of the file. Each choice of DataNodes is likely to be different. The interactions among the client, the NameNode and the DataNodes are illustrated in Fig. 1. Unlike conventional file systems, HDFS provides an API that exposes the locations of a file blocks. This allows applications like the MapReduce framework to schedule a task to where the data are located, thus improving the read performance. It also allows an application to set the replication factor of a file. By default, a file's replication factor is three. For critical files or files which are accessed very often, having a higher replication factor improves their tolerance against faults and increase their read bandwidth.

Image and Journal

The namespace image is the file system metadata that describes the organization of application data as directories and files. A persistent record of the image written to disk is called a checkpoint. The journal is a write-ahead commit log for changes to the file system that must be persistent. For each client-initiated transaction, the change is recorded in the journal, and the journal file is flushed and synched before the change is committed to the HDFS client. The checkpoint file is never changed by the NameNode; it is replaced in its entirety when a new checkpoint is created during restart, when requested by the administrator, or by the CheckpointNode described in the next section. During startup the NameNode initializes the namespace image from the checkpoint, and then replays changes from the journal until the image is up-to-date with the last state of the file system. A new checkpoint and empty journal are written back to the storage directories before the NameNode starts serving clients. If either the checkpoint or the journal is missing, or becomes corrupt, the namespace information will be lost partly or entirely. In order to preserve this critical information HDFS can be configured to store the checkpoint and journal in multiple storage directories. Recommended practice is to place the directories on different volumes, and for one storage directory to be on a remote NFS server. The first choice prevents loss from single volume failures, and the second choice protects against failure of the entire node. If the NameNode encounters an error writing the journal to one of the storage directories it automatically excludes that directory from the list of storage directories. The NameNode automatically shuts itself down if no storage directory is available. The NameNode is a multithreaded system and processes requests simultaneously from multiple clients. Saving a transaction to disk becomes a bottleneck since all other threads need to wait until the synchronous flush-and-sync procedure initiated by one of them is complete. In order to optimize this process, the NameNode batches multiple transactions initiated by different clients. When one of the NameNode's threads initiates a flush-and-sync operation, all transactions batched at that time are committed together. Remaining threads only need to check that their transactions have been saved and do not need to initiate a flush-and-sync operation.

CheckpointNode

The NameNode in HDFS, in addition to its primary role serving client requests, can alternatively execute either of two other roles, either a CheckpointNode or a BackupNode. The role is specified at the node startup. The CheckpointNode periodically combines the existing checkpoint and journal to create a new checkpoint and an empty journal. The CheckpointNode usually runs on a different host from the NameNode since it has the same memory requirements as the NameNode. It downloads the current checkpoint and journal files from the NameNode, merges them locally, and returns the new checkpoint back to the NameNode.

BackupNode

A recently introduced feature of HDFS is the BackupNode. Like a CheckpointNode, the BackupNode is capable of creating periodic checkpoints, but in addition it maintains an inmemory, up-to-date image of the file system namespace that is always synchronized with the state of the NameNode. The BackupNode accepts the journal stream of namespace transactions from the active NameNode, saves them to its own storage directories, and applies these transactions to its own namespace image in memory. The NameNode treats the BackupNode as a journal store the same as it treats journal files in its storage directories. If the NameNode fails, the BackupNode's image in memory and the checkpoint on disk is a record of the latest namespace state. The BackupNode can create a checkpoint without downloading checkpoint and journal files from the active NameNode, since it already has an up-to-date namespace image in its memory. This makes the checkpoint process on the BackupNode more efficient as it only needs to save the namespace into its local storage directories. The BackupNode can be viewed as a read-only NameNode. It contains all file system metadata information except for block locations. It can perform all operations of the regular NameNode that do not involve modification of the namespace or knowledge of block locations. Use of a BackupNode provides the option of running the NameNode without persistent storage, delegating responsibility for the namespace state persisting to the BackupNode.

FILE I/O OPERATIONS AND REPLICA MANGEMENT

File Read and Write

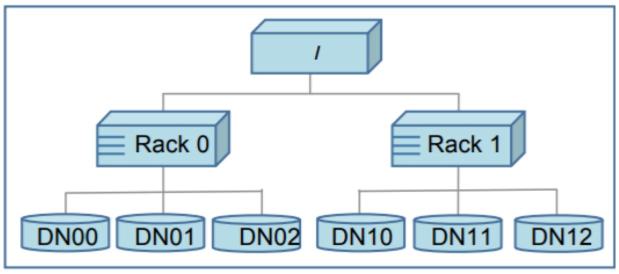
An application adds data to HDFS by creating a new file and writing the data to it. After the file is closed, the bytes written cannot be altered or removed except that new data can be added to the file by reopening the file for append. HDFS implements a single-writer, multiple-reader model. The HDFS client that opens a file for writing is granted a lease for the file; no other client can write to the file. The writing client periodically renews the lease by sending a heartbeat to the NameNode. When the file is closed, the lease is revoked. 5 The lease duration is bound by a soft limit and a hard limit. Until the soft limit expires, the writer is certain of exclusive access to the file. If the soft limit expires and the client fails to close the file or renew the lease, another client can preempt the lease. If after the hard limit expires (one hour) and the client has failed to renew the lease, HDFS assumes that the client has quit and will automatically close the file on behalf of the writer, and recover the lease. The writer's lease does not prevent other clients from reading the file; a file may have many concurrent readers. An HDFS file consists of blocks. When there is a need for a new block, the NameNode allocates a block with a unique block ID and determines a list of DataNodes to host replicas of the block. The DataNodes form a pipeline, the order of which minimizes the total network distance from the client to the last DataNode.

Bytes are pushed to the pipeline as a sequence of packets. The bytes that an application writes first buffer at the client side. After a packet buffer is filled (typically 64 KB), the data are pushed to the pipeline. The next packet can be pushed to the pipeline before receiving the acknowledgement for the previous packets. The number of outstanding packets is limited by the outstanding packets window size of the client. After data are written to an HDFS file, HDFS does not provide any guarantee that data are visible to a new reader until the file is closed. If a user application needs the visibility guarantee, it can explicitly call the hflush operation. Then the current packet is immediately pushed to the pipeline, and the hflush operation will wait until all DataNodes in the pipeline acknowledge the successful transmission of the packet. All data written before the hflush operation are then certain to be visible to readers.

In a cluster of thousands of nodes, failures of a node (most commonly storage faults) are daily occurrences. A replica stored on a DataNode may become corrupted because of faults in memory, disk, or network. HDFS generates and stores checksums for each data block of an HDFS file. Checksums are verified by the HDFS client while reading to help detect any corruption caused either by client, DataNodes, or network. When a client creates an HDFS file, it computes the checksum sequence for each block and sends it to a DataNode along with the data. A DataNode stores checksums in a metadata file separate from the block's data file. When HDFS reads a file, each block's data and checksums are shipped to the client. The client computes the checksum for the received data and verifies that the newly computed checksums matches the checksums it received. If not, the client notifies the NameNode of the corrupt replica and then fetches a different replica of the block from another DataNode. When a client opens a file to read, it fetches the list of blocks and the locations of each block replica from the NameNode. The locations of each block are ordered by their distance from the reader. When reading the content of a block, the client tries the closest replica first. If the read attempt fails, the client tries the next replica in sequence. A read may fail if the target DataNode is unavailable, the node no longer hosts a replica of the block, or the replica is found to be corrupt when checksums are tested. HDFS permits a client to read a file that is open for writing. When reading a file open for writing, the length of the last block still being written is unknown to the NameNode. In this case, the client asks one of the replicas for the latest length before starting to read its content. The design of HDFS I/O is particularly optimized for batch processing systems, like MapReduce, which require high throughput for sequential reads and writes. However, many efforts have been put to improve its read/write response time in order to support applications like Scribe that provide real-time data streaming to HDFS, or HBase that provides random, realtime access to large tables.

Block Placement

For a large cluster, it may not be practical to connect all nodes in a flat topology. A common practice is to spread the nodes across multiple racks. Nodes of a rack share a switch, and rack switches are connected by one or more core switches. Communication between two nodes in different racks has to go through multiple switches. In most cases, network bandwidth 6 between nodes in the same rack is greater than network bandwidth between nodes in different racks. Fig. below describes a cluster with two racks, each of which contains three nodes.



Conclusion

The Hadoop cluster is effectively unavailable when its NameNode is down. Given that Hadoop is used primarily as a batch system, restarting the NameNode has been a satisfactory recovery means. However, we have taken steps towards automated failover. Currently a BackupNode receives all transactions from the primary NameNode. This will allow a failover to a warm or even a hot BackupNode if we send block reports to both the primary NameNode and BackupNode. A few Hadoop users outside Yahoo! have experimented with manual failover. Our plan is to use Zookeeper, Yahoo's distributed consensus technology to build an automated failover solution. The main drawback of multiple independent namespaces is the cost of managing them, especially if the number of namespaces is large. We are also planning to use application or job centric namespaces rather than cluster centric namespaces— this is analogous to the per-process namespaces that are used to deal with remote execution in distributed systems in the late 80s and early 90s

References

- Konstantin Shvachko, Hairong Kuang, Sanjay Radia, Robert Chansler, Sunnyvale, California USA