CHAPTER 7

How MapReduce Works

In this chapter, we look at how MapReduce in Hadoop works in detail. This knowledge provides a good foundation for writing more advanced MapReduce programs, which we will cover in the following two chapters.

Anatomy of a MapReduce Job Run

You can run a MapReduce job with a single method call: `submit()` on a `Job` object (you can also call `waitForCompletion()`, which submits the job if it hasn't been submitted already, then waits for it to finish).[1] This method call conceals a great deal of processing behind the scenes. This section uncovers the steps Hadoop takes to run a job.

The whole process is illustrated in Figure 7-1. At the highest level, there are five independent entities:[2]

- The client, which submits the MapReduce job.
- The YARN resource manager, which coordinates the allocation of compute resources on the cluster.
- The YARN node managers, which launch and monitor the compute containers on machines in the cluster.
- The MapReduce application master, which coordinates the tasks running the MapReduce job. The application master and the MapReduce tasks run in containers that are scheduled by the resource manager and managed by the node managers.

1. In the old MapReduce API, you can call `JobClient.submitJob(conf)` or `JobClient.runJob(conf)`.
2. Not discussed in this section are the job history server daemon (for retaining job history data) and the shuffle handler auxiliary service (for serving map outputs to reduce tasks).

- The distributed filesystem (normally HDFS, covered in Chapter 3), which is used for sharing job files between the other entities.

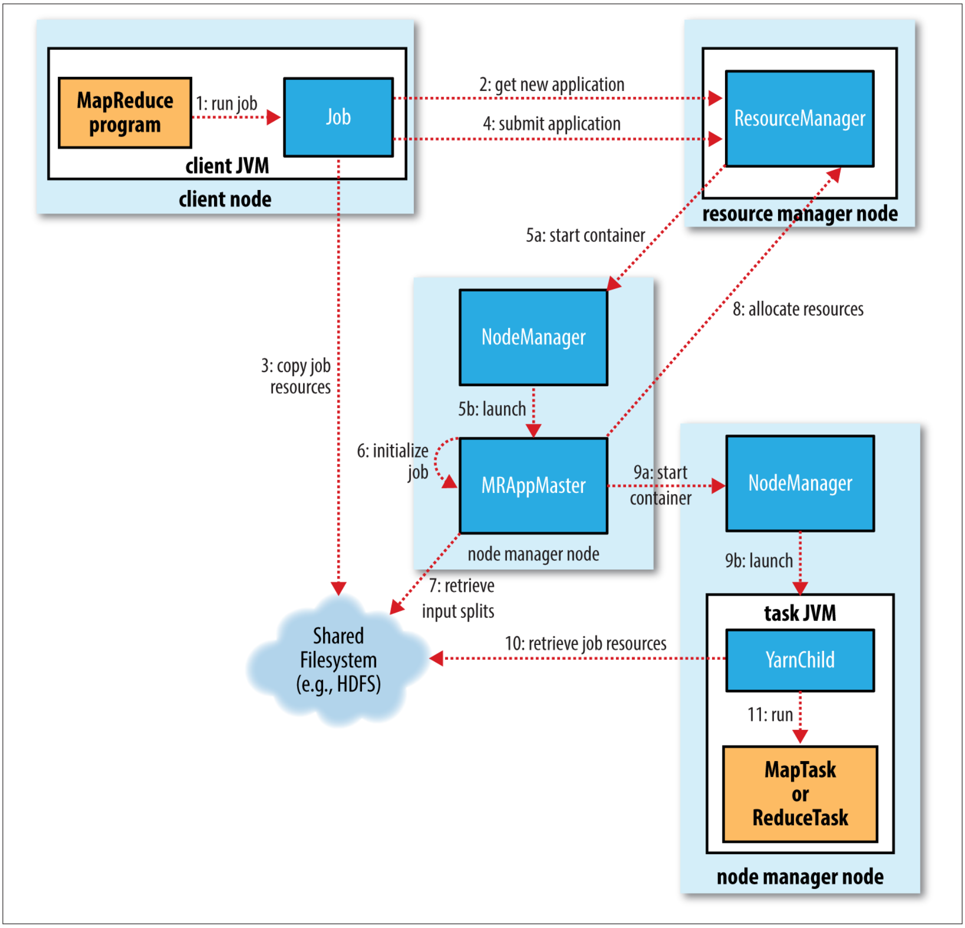

Figure 7-1. How Hadoop runs a MapReduce job

Job Submission

The `submit()` method on `Job` creates an internal `JobSubmitter` instance and calls `submitJobInternal()` on it (step 1 in Figure 7-1). Having submitted the job, `waitForCompletion()` polls the job's progress once per second and reports the progress to the console if it has changed since the last report. When the job completes successfully, the job counters are displayed. Otherwise, the error that caused the job to fail is logged to the console.

The job submission process implemented by `JobSubmitter` does the following:

- Asks the resource manager for a new application ID, used for the MapReduce job ID (step 2).
- Checks the output specification of the job. For example, if the output directory has not been specified or it already exists, the job is not submitted and an error is thrown to the MapReduce program.
- Computes the input splits for the job. If the splits cannot be computed (because the input paths don't exist, for example), the job is not submitted and an error is thrown to the MapReduce program.
- Copies the resources needed to run the job, including the job JAR file, the configuration file, and the computed input splits, to the shared filesystem in a directory named after the job ID (step 3). The job JAR is copied with a high replication factor (controlled by the `mapreduce.client.submit.file.replication` property, which defaults to 10) so that there are lots of copies across the cluster for the node managers to access when they run tasks for the job.
- Submits the job by calling `submitApplication()` on the resource manager (step 4).

Job Initialization

When the resource manager receives a call to its `submitApplication()` method, it hands off the request to the YARN scheduler. The scheduler allocates a container, and the resource manager then launches the application master's process there, under the node manager's management (steps 5a and 5b).

The application master for MapReduce jobs is a Java application whose main class is `MRAppMaster`. It initializes the job by creating a number of bookkeeping objects to keep track of the job's progress, as it will receive progress and completion reports from the tasks (step 6). Next, it retrieves the input splits computed in the client from the shared filesystem (step 7). It then creates a map task object for each split, as well as a number of reduce task objects determined by the `mapreduce.job.reduces` property (set by the `setNumReduceTasks()` method on `Job`). Tasks are given IDs at this point.

The application master must decide how to run the tasks that make up the MapReduce job. If the job is small, the application master may choose to run the tasks in the same JVM as itself. This happens when it judges that the overhead of allocating and running tasks in new containers outweighs the gain to be had in running them in parallel, compared to running them sequentially on one node. Such a job is said to be *uberized*, or run as an *uber task*.

What qualifies as a small job? By default, a small job is one that has less than 10 mappers, only one reducer, and an input size that is less than the size of one HDFS block. (Note that these values may be changed for a job by setting `mapreduce.job.ubertask.maxmaps`, `mapreduce.job.ubertask.maxreduces`, and `mapreduce.job.ubertask.maxbytes`.) Uber tasks must be enabled explicitly (for an individual job, or across the cluster) by setting `mapreduce.job.ubertask.enable` to `true`.

Finally, before any tasks can be run, the application master calls the `setupJob()` method on the `OutputCommitter`. For `FileOutputCommitter`, which is the default, it will create the final output directory for the job and the temporary working space for the task output. The commit protocol is described in more detail in "Output Committers" on page 206.

Task Assignment

If the job does not qualify for running as an uber task, then the application master requests containers for all the map and reduce tasks in the job from the resource manager (step 8). Requests for map tasks are made first and with a higher priority than those for reduce tasks, since all the map tasks must complete before the sort phase of the reduce can start (see "Shuffle and Sort" on page 197). Requests for reduce tasks are not made until 5% of map tasks have completed (see "Reduce slow start" on page 308).

Reduce tasks can run anywhere in the cluster, but requests for map tasks have data locality constraints that the scheduler tries to honor (see "Resource Requests" on page 81). In the optimal case, the task is *data local*—that is, running on the same node that the split resides on. Alternatively, the task may be *rack local*: on the same rack, but not the same node, as the split. Some tasks are neither data local nor rack local and retrieve their data from a different rack than the one they are running on. For a particular job run, you can determine the number of tasks that ran at each locality level by looking at the job's counters (see Table 9-6).

Requests also specify memory requirements and CPUs for tasks. By default, each map and reduce task is allocated 1,024 MB of memory and one virtual core. The values are configurable on a per-job basis (subject to minimum and maximum values described in "Memory settings in YARN and MapReduce" on page 301) via the following properties: `mapreduce.map.memory.mb`, `mapreduce.reduce.memory.mb`, `mapreduce.map.cpu.vcores` and `mapreduce.reduce.cpu.vcores`.

Task Execution

Once a task has been assigned resources for a container on a particular node by the resource manager's scheduler, the application master starts the container by contacting the node manager (steps 9a and 9b). The task is executed by a Java application whose main class is `YarnChild`. Before it can run the task, it localizes the resources that the task needs, including the job configuration and JAR file, and any files from the distributed cache (step 10; see "Distributed Cache" on page 274). Finally, it runs the map or reduce task (step 11).

The `YarnChild` runs in a dedicated JVM, so that any bugs in the user-defined map and reduce functions (or even in `YarnChild`) don't affect the node manager—by causing it to crash or hang, for example.

Each task can perform setup and commit actions, which are run in the same JVM as the task itself and are determined by the `OutputCommitter` for the job (see "Output Committers" on page 206). For file-based jobs, the commit action moves the task output from a temporary location to its final location. The commit protocol ensures that when speculative execution is enabled (see "Speculative Execution" on page 204), only one of the duplicate tasks is committed and the other is aborted.

Streaming

Streaming runs special map and reduce tasks for the purpose of launching the user-supplied executable and communicating with it (Figure 7-2).

The Streaming task communicates with the process (which may be written in any language) using standard input and output streams. During execution of the task, the Java process passes input key-value pairs to the external process, which runs it through the user-defined map or reduce function and passes the output key-value pairs back to the Java process. From the node manager's point of view, it is as if the child process ran the map or reduce code itself.

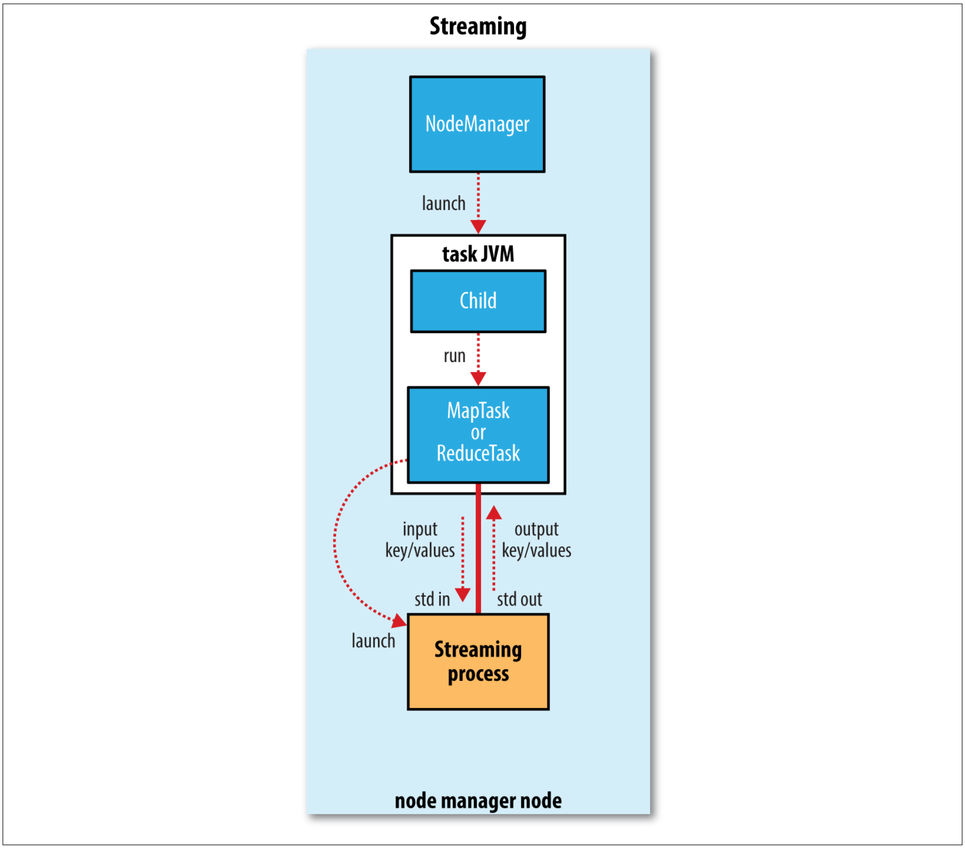

Figure 7-2. The relationship of the Streaming executable to the node manager and the task container

Progress and Status Updates

MapReduce jobs are long-running batch jobs, taking anything from tens of seconds to hours to run. Because this can be a significant length of time, it's important for the user to get feedback on how the job is progressing. A job and each of its tasks have a *status*, which includes such things as the state of the job or task (e.g., running, successfully completed, failed), the progress of maps and reduces, the values of the job's counters, and a status message or description (which may be set by user code). These statuses change over the course of the job, so how do they get communicated back to the client?

When a task is running, it keeps track of its *progress* (i.e., the proportion of the task completed). For map tasks, this is the proportion of the input that has been processed. For reduce tasks, it's a little more complex, but the system can still estimate the proportion of the reduce input processed. It does this by dividing the total progress into three parts, corresponding to the three phases of the shuffle (see "Shuffle and Sort" on page 197). For example, if the task has run the reducer on half its input, the task's progress is 5/6, since it has completed the copy and sort phases (1/3 each) and is halfway through the reduce phase (1/6).

What Constitutes Progress in MapReduce?

Progress is not always measurable, but nevertheless, it tells Hadoop that a task is doing something. For example, a task writing output records is making progress, even when it cannot be expressed as a percentage of the total number that will be written (because the latter figure may not be known, even by the task producing the output).

Progress reporting is important, as Hadoop will not fail a task that's making progress. All of the following operations constitute progress:

- Reading an input record (in a mapper or reducer)
- Writing an output record (in a mapper or reducer)
- Setting the status description (via `Reporter`'s or `TaskAttemptContext`'s `setStatus()` method)
- Incrementing a counter (using `Reporter`'s `incrCounter()` method or `Counter`'s `increment()` method)
- Calling `Reporter`'s or `TaskAttemptContext`'s `progress()` method

Tasks also have a set of counters that count various events as the task runs (we saw an example in "A test run" on page 27), which are either built into the framework, such as the number of map output records written, or defined by users.

As the map or reduce task runs, the child process communicates with its parent application master through the *umbilical* interface. The task reports its progress and status (including counters) back to its application master, which has an aggregate view of the job, every three seconds over the umbilical interface.

The resource manager web UI displays all the running applications with links to the web UIs of their respective application masters, each of which displays further details on the MapReduce job, including its progress.

During the course of the job, the client receives the latest status by polling the application master every second (the interval is set via `mapreduce.client.progressmonitor.pollinterval`). Clients can also use `Job`'s `getStatus()` method to obtain a `JobStatus` instance, which contains all of the status information for the job.

The process is illustrated in Figure 7-3.

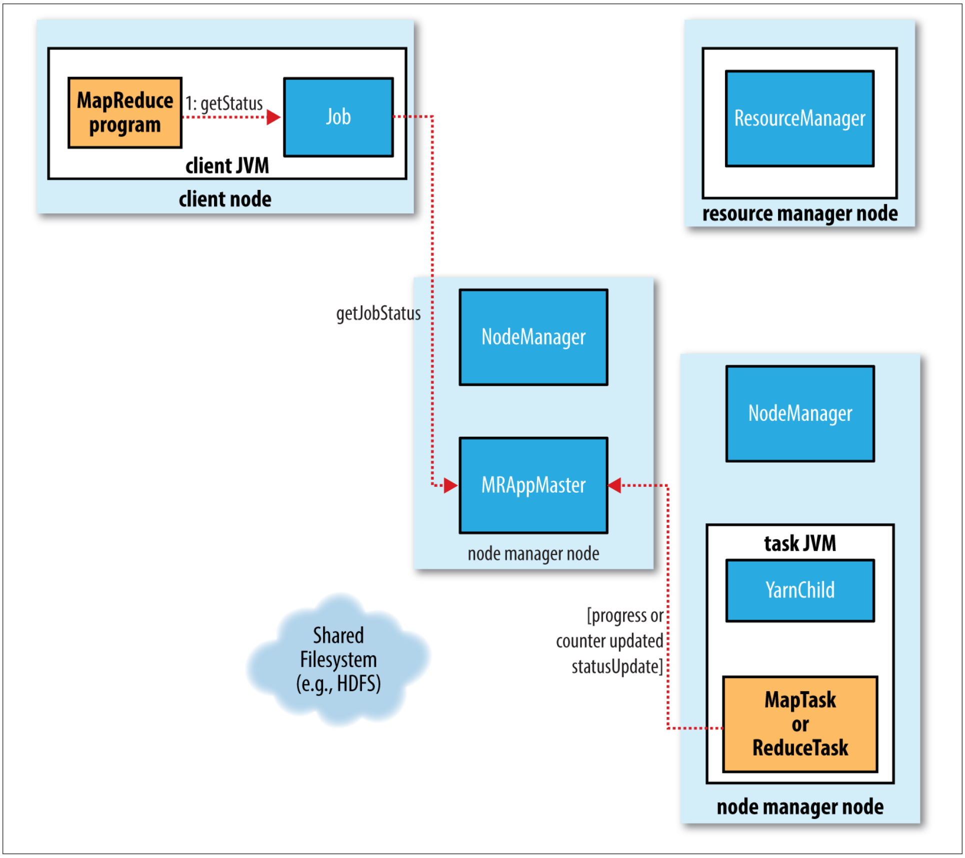

Figure 7-3. How status updates are propagated through the MapReduce system

Job Completion

When the application master receives a notification that the last task for a job is complete, it changes the status for the job to "successful." Then, when the `Job` polls for status, it learns that the job has completed successfully, so it prints a message to tell the user and then returns from the `waitForCompletion()` method. Job statistics and counters are printed to the console at this point.

The application master also sends an HTTP job notification if it is configured to do so. This can be configured by clients wishing to receive callbacks, via the `mapreduce.job.end-notification.url` property.

Finally, on job completion, the application master and the task containers clean up their working state (so intermediate output is deleted), and the `OutputCommitter`'s `commitJob()` method is called. Job information is archived by the job history server to enable later interrogation by users if desired.