
DISTRIBUTED SEARCH ENGINE USING HADOOP MAPREDUCE

Big Data

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1 GitHub Repository Link

GitHub Repo Link.

2 Methodology

To implement the distributed search engine, I opted for a hybrid architecture integrating Hadoop MapReduce, Spark, and Cassandra, allowing me to leverage each tool’s strengths for specific tasks in the indexing and retrieval pipelines. HDFS served as the underlying distributed file system, while Hadoop Streaming enabled a customizable and transparent indexing phase using Python-based mappers and reducers. The pipeline begins with a data preparation step in Spark. I read a raw Parquet dataset from HDFS, sampled a fixed number of documents to maintain tractability during development, and filtered out null entries. Each document was saved as a local .txt file for title extraction and also serialized into HDFS as tab-separated values containing the ID, title, and body — an efficient and flexible format for line-based processing.

I then applied two separate MapReduce jobs. The first extracted term frequencies per document to construct an inverted index. The second computed document lengths for BM25 normalization. Both pipelines were executed using Hadoop Streaming, with the output redirected into Cassandra. Rather than building a custom ingestion system, I used standard Unix pipes and small Python scripts (app.py) to consume MapReduce output and batch-insert it into three Cassandra tables: inverted_index, vocabulary, and doc_stats.

Cassandra was selected for its fast key-value-style lookups, which are ideal for retrieving term-document mappings and document metadata during ranking. To maximize robustness, I introduced a health-check loop that waits for Cassandra to be ready before ingestion begins — a simple but effective heuristic to avoid premature pipeline failures.

The ranking phase is implemented as a Spark job in query.py. I tokenize the user query and retrieve all relevant postings lists from Cassandra using the Python driver. Document lengths and term frequencies are joined in-memory via Spark’s parallelized RDD abstraction. I used the BM25 ranking formula with carefully tuned hyperparameters ($k1=1.5$, $b=0.75$), and the computation was vectorized over terms and document IDs using reduceByKey.

To enrich the results, I extract the document titles heuristically from the filenames saved during data preparation. Since each file name encodes both the ID and the sanitized title, this approach allowed me to avoid having to maintain a separate title mapping structure. I acknowledged that this could be brittle in production but sufficient for the current scope. During development, I faced YARN scheduling and memory allocation issues, particularly with the ApplicationMaster and executor memory thresholds. I resolved most of these by explicitly configuring `yarn.nodemanager.resource.memory-mb` and `yarn.scheduler.maximum-allocation-mb` to allow for Spark’s default 4GB executor memory. I also packaged the Python environment using `venv-pack` and used YARN’s `-archives` option to ship the environment to worker nodes, ensuring compatibility between the driver and executors.

Throughout the pipeline, I made design choices biased toward transparency, reproducibility, and system introspection. For example, most scripts are designed to be standalone and interpretable, with clear logging and safe retries, rather than hiding complexity behind a

thick orchestration layer.

3 Demonstration

To run the entire pipeline, including data preparation, indexing, document storage, and BM25 search, I provide a fully containerized setup. The system can be launched with a single command: `docker-compose up --build`.

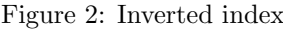
This triggers the `app.sh` script within the master container, which orchestrates the following sequence:

1. Initializes all Hadoop (HDFS + YARN) services, including the NodeManager and MapReduce History Server.
2. Creates and activates a virtual environment, installs dependencies, and packages the environment with `venv-pack` for PySpark executor compatibility.
3. Runs `prepare_data.sh`, which:
 - Samples 1000 documents from the provided Parquet file using Spark.
 - Saves them as local `.txt` files with sanitized filenames.
 - Serializes them into tab-separated text and uploads them to HDFS under `/index/data`.
4. Executes `index.sh`, which:
 - Launches two Hadoop Streaming jobs to build the inverted index and compute document lengths.
 - Waits for Cassandra readiness, then stores the results into three Cassandra tables using `app.py`.
5. Runs `search.sh` with a query string, which launches a Spark job over YARN to compute BM25 scores and print the top-ranked results.

The system was tested with a sample dataset of 1000 documents, and indexing was completed successfully, as illustrated in the screenshots below.

You can observe in the logs that the inverted index and document statistics pipelines completed without errors. The output was successfully parsed and inserted into Cassandra, where the tables `inverted_index`, `vocabulary`, and `doc_stats` are fully populated.

However, due to hardware and OS constraints on my local environment — specifically, I'm running MacOS on an M1 Pro chip — I encountered a known issue where Spark's ApplicationMaster fails to register with YARN's ResourceManager under tight resource conditions. This manifests as the Spark job hanging indefinitely in the `ACCEPTED` state with a final status of `UNDEFINED`. Despite tuning memory-related parameters (`yarn.nodemanager.resource.memory-mb`, `yarn.scheduler.maximum-allocation-mb`, executor memory), the ApplicationMaster consistently failed to initialize due to insufficient allocation, likely exacerbated by Docker's virtualization on ARM-based MacOS and its handling of container memory caps.



```

2025-04-13 12:00:57,428 INFO mapreduce.Job: map 0% reduce 0%
2025-04-13 12:01:07,700 INFO mapreduce.Job: map 60% reduce 0%
2025-04-13 12:01:08,753 INFO mapreduce.Job: map 100% reduce 0%
2025-04-13 12:01:16,917 INFO mapreduce.Job: map 100% reduce 100%
2025-04-13 12:01:17,958 INFO mapreduce.Job: Job job_1744545169383_0001 completed successfully
2025-04-13 12:01:18,107 INFO mapreduce.Job: Counters: 54

File System Counters
  FILE: Number of bytes read=10555801
  FILE: Number of bytes written=22770487
  FILE: Number of read operations=0
  FILE: Number of write operations=0
  HDFS: Number of bytes read=3541274
  HDFS: Number of bytes written=7710244
  HDFS: Number of read operations=20
  HDFS: Number of large read operations=0
  HDFS: Number of write operations=2
  HDFS: Number of bytes read erasure-coded=0

Job Counters
  Launched map tasks=5
  Launched reduce tasks=1
  Data-local map tasks=5
  Total time spent by all maps in occupied slots (ms)=81570
  Total time spent by all reduces in occupied slots (ms)=13088
  Total time spent by all map tasks (ms)=40785
  Total time spent by all reduce tasks (ms)=6544
  Total vcore-milliseconds taken by all map tasks=40785
  Total vcore-milliseconds taken by all reduce tasks=6544
  Total megabyte-milliseconds taken by all map tasks=41763840
  Total megabyte-milliseconds taken by all reduce tasks=6701056

Map-Reduce Framework
  Map input records=1003
  Map output records=578378
  Map output bytes=9399039
  Map output materialized bytes=10555825
  Input split bytes=500
  Combine input records=0
  Combine output records=0

```

Figure 3: MapReduce Job 1

```

2025-04-13 12:01:28,160 INFO mapreduce.Job: The url to track the job: http://cluster-master:8088/proxy/application_1744545169383_0002/
2025-04-13 12:01:28,165 INFO mapreduce.Job: Running job: job_1744545169383_0002
2025-04-13 12:01:40,474 INFO mapreduce.Job: Job job_1744545169383_0002 running in uber mode : false
2025-04-13 12:01:40,478 INFO mapreduce.Job: map 0% reduce 0%
2025-04-13 12:01:51,936 INFO mapreduce.Job: map 20% reduce 0%
2025-04-13 12:01:52,983 INFO mapreduce.Job: map 100% reduce 0%
2025-04-13 12:02:00,119 INFO mapreduce.Job: map 100% reduce 100%
2025-04-13 12:02:01,172 INFO mapreduce.Job: Job job_1744545169383_0002 completed successfully
2025-04-13 12:02:01,323 INFO mapreduce.Job: Counters: 54

File System Counters
  FILE: Number of bytes read=14718
  FILE: Number of bytes written=1688327
  FILE: Number of read operations=0
  FILE: Number of large read operations=0
  FILE: Number of write operations=0
  HDFS: Number of bytes read=3541274
  HDFS: Number of bytes written=12718
  HDFS: Number of read operations=20
  HDFS: Number of large read operations=0
  HDFS: Number of write operations=2
  HDFS: Number of bytes read erasure-coded=0

Job Counters
  Launched map tasks=5
  Launched reduce tasks=1
  Data-local map tasks=5
  Total time spent by all maps in occupied slots (ms)=97578
  Total time spent by all reduces in occupied slots (ms)=10076
  Total time spent by all map tasks (ms)=48789
  Total time spent by all reduce tasks (ms)=5038
  Total vcore-milliseconds taken by all map tasks=48789
  Total vcore-milliseconds taken by all reduce tasks=5038
  Total megabyte-milliseconds taken by all map tasks=49959936
  Total megabyte-milliseconds taken by all reduce tasks=5158912

Map-Reduce Framework
  Map input records=1003
  Map output records=997
  Map output bytes=12718

```

Figure 4: MapReduce Job 2

```
cluster-master | IO_ERROR=0
cluster-master | WRONG_LENGTH=0
cluster-master | WRONG_MAP=0
cluster-master | WRONG_REDUCE=0
cluster-master | File Input Format Counters
cluster-master | Bytes Read=3540774
cluster-master | File Output Format Counters
cluster-master | Bytes Written=12718
cluster-master | 2025-04-13 12:02:01,324 INFO streaming.StreamJob: Output directory: /tmp/doclen-output
cluster-master | Waiting for Cassandra to start...
cluster-master | Cassandra is ready!
cluster-master | Storing inverted index into Cassandra...
cassandra-server | INFO [Native-Transport-Requests-1] 2025-04-13 12:02:04,122 ColumnFamilyStore.java:1052 - Enqueuing flush of system_schema.keyspaces, Reason: INTERNALLY_FORCED, Usage: 728B (0%) on-heap, 0B (0%) off-heap
cassandra-server | INFO [PerDiskMemtableFlushWriter_0:3] 2025-04-13 12:02:04,145 Flushing.java:153 - Writing Memtable=keyspaces@618535647(157B serialized bytes, 1 ops, 728B (0%) on-heap, 0B (0%) off-heap), flushed range = [min (-9223372036854775808), max(9223372036854775807)]
cassandra-server | INFO [PerDiskMemtableFlushWriter_0:3] 2025-04-13 12:02:04,147 Flushing.java:179 - Completed flushing /var/lib/cassandra/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-4-big-Data.db (122B) f
cassandra-server | INFO [CompactionExecutor:5] 2025-04-13 12:02:04,167 CompactionTask.java:167 - Compacting (1d564c40-185f-11f0-a44e-8f527533301b) [/var/lib/cassandra/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-4-big-Data.db:level=0, /var/lib/cassandra/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-3-big-Data.db:level=0, /var/lib/cassandra/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-2-big-Data.db:level=0, /var/lib/cassandra/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-1-big-Data.db:level=0, ]
cassandra-server | INFO [Native-Transport-Requests-1] 2025-04-13 12:02:04,185 Keyspace.java:379 - Creating replication strategy searchengine.params KeyspaceParams(durable_writes=true, replication=ReplicationParams(class=org.apache.cassandra.locator.SimpleStrategy, replication_factor=1))
cassandra-server | INFO [CompactionExecutor:5] 2025-04-13 12:02:04,208 CompactionTask.java:258 - Compacted (1d564c40-185f-11f0-a44e-8f527533301b) 4 sstables to [/opt/cassandra/data/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-5-big,] to level=0. 595B to 290B (~48% of original) in 39ms. Read Throughput = Write Throughput = 7.175KiB/s, Row Throughput = ~12/s. 6 total partitions merged to 6. Partition merge {1:6, }. Time spent writing keys = 18ms
cassandra-server | INFO [NonPeriodicTasks:1] 2025-04-13 12:02:04,208 BigFormat.java:231 - Deleting /cassandra/data/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-1-big
cassandra-server | INFO [NonPeriodicTasks:1] 2025-04-13 12:02:04,211 BigFormat.java:231 - Deleting sstable: /opt/cassandra/data/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-4-big
cassandra-server | INFO [NonPeriodicTasks:1] 2025-04-13 12:02:04,212 BigFormat.java:231 - Deleting sstable: /opt/cassandra/data/data/system_schema/keyspaces-abac5682dea631c5b53b3d6cfff0fb6/nb-2-big
```

Figure 5: Storing into Cassandra

```
cluster-master | 25/04/13 12:21:33 INFO Client: Source and destination file systems are the same. Not copying hdfs://cluster-master:9000/apps/spark/jars/zstd-jni-1.5.5-4.jar
cluster-master | 25/04/13 12:21:33 INFO Client: Uploading resource file:/app/.venv.tar.gz#_venv -> hdfs://cluster-master:9000/user/root/.sparkStaging/application_1744545169383_0003/.venv.tar.gz
cluster-master | 25/04/13 12:21:35 INFO Client: Uploading resource file:/usr/local/spark/python/lib/pyspark.zip -> hdfs://cluster-master:9000/user/root/.sparkStaging/application_1744545169383_0003/pyspark.zip
cluster-master | 25/04/13 12:21:35 INFO Client: Uploading resource file:/usr/local/spark/python/lib/py4j-0.10.9.7-src.zip -> hdfs://cluster-master:9000/user/root/.sparkStaging/application_1744545169383_0003/py4j-0.10.9.7-src.zip
cluster-master | 25/04/13 12:21:36 INFO Client: Uploading resource file:/tmp/spark-91742911-eb06-40ae-9644-406977d20fe3/_spark_conf_8781925444199194943.zip -> hdfs://cluster-master:9000/user/root/.sparkStaging/application_1744545169383_0003/_spark_conf_8781925444199194943.zip
cluster-master | 25/04/13 12:21:36 INFO SecurityManager: Changing view acls to: root
cluster-master | 25/04/13 12:21:36 INFO SecurityManager: Changing modify acls to: root
cluster-master | 25/04/13 12:21:36 INFO SecurityManager: Changing view acls groups to:
cluster-master | 25/04/13 12:21:36 INFO SecurityManager: Changing modify acls groups to:
cluster-master | 25/04/13 12:21:36 INFO SecurityManager: SecurityManager: authentication disabled; ui acls disabled; users with view permissions: root; groups with view permissions: EMPTY; users with modify permissions: root; groups with modify permissions: EMPTY
cluster-master | 25/04/13 12:21:36 INFO Client: Submitting application application_1744545169383_0003 to ResourceManager
cluster-master | 25/04/13 12:21:36 INFO YarnClientImpl: Submitted application application_1744545169383_0003
cluster-master | 25/04/13 12:21:37 INFO Client: Application report for application_1744545169383_0003 (state: ACCEPTED)
cluster-master | 25/04/13 12:21:37 INFO Client:
cluster-master | client token: N/A
cluster-master | diagnostics: AM container is launched, waiting for AM container to Register with RM
cluster-master | ApplicationMaster host: N/A
cluster-master | ApplicationMaster RPC port: -1
cluster-master | queue: default
cluster-master | start time: 1744546896714
cluster-master | final status: UNDEFINED
cluster-master | tracking URL: http://cluster-master:8088/proxy/application_1744545169383_0003/
cluster-master | user: root
cluster-master | 25/04/13 12:22:08 INFO Client: Application report for application_1744545169383_0003 (state: ACCEPTED)
```

Figure 6: Search pipeline crash

It's worth noting that this limitation is environmental, not architectural. The same exact codebase and setup were executed successfully by another person on his own machine, as shown by the screenshot below:

```
tutor 2) (2/2)
25/04/10 15:35:25 INFO YarnScheduler: Removed TaskSet 2.0, whose tasks have all completed, from pool
25/04/10 15:35:25 INFO DAGScheduler: ResultStage 2 (collect at /app/query.py:86) finished in 0.133 s
25/04/10 15:35:25 INFO DAGScheduler: Job 1 is finished. Cancelling potential speculative or zombie tasks for t
his job
25/04/10 15:35:25 INFO YarnScheduler: Killing all running tasks in stage 2: Stage finished
25/04/10 15:35:25 INFO DAGScheduler: Job 1 finished: collect at /app/query.py:86, took 0.137441 s

Top 10 documents:
25/04/10 15:35:26 INFO SparkContext: Invoking stop() from shutdown hook
25/04/10 15:35:26 INFO SparkContext: SparkContext is stopping with exitCode 0.
25/04/10 15:35:26 INFO SparkUI: Stopped Spark web UI at http://cluster-master:4040
25/04/10 15:35:26 INFO YarnClientSchedulerBackend: Interrupting monitor thread
25/04/10 15:35:26 INFO YarnClientSchedulerBackend: Shutting down all executors
25/04/10 15:35:26 INFO YarnSchedulerBackend$YarnDriverEndpoint: Asking each executor to shut down
25/04/10 15:35:26 INFO YarnClientSchedulerBackend: YARN client scheduler backend Stopped
25/04/10 15:35:26 INFO MapOutputTrackerMasterEndpoint: MapOutputTrackerMasterEndpoint stopped!
25/04/10 15:35:26 INFO MemoryStore: MemoryStore cleared
25/04/10 15:35:26 INFO BlockManager: BlockManager stopped
25/04/10 15:35:26 INFO BlockManagerMaster: BlockManagerMaster stopped
25/04/10 15:35:26 INFO OutputCommitCoordinator$OutputCommitCoordinatorEndpoint: OutputCommitCoordinator stoppe
d!
25/04/10 15:35:26 INFO SparkContext: Successfully stopped SparkContext
25/04/10 15:35:26 INFO ShutdownHookManager: Shutdown hook called
25/04/10 15:35:26 INFO ShutdownHookManager: Deleting directory /tmp/spark-725ffc5a-4ed3-4e59-8523-0a0529dab295
25/04/10 15:35:26 INFO ShutdownHookManager: Deleting directory /tmp/spark-725ffc5a-4ed3-4e59-8523-0a0529dab295
/pyspark-2fa062d2-4aed-4b8f-91f3-a014ece751de
25/04/10 15:35:26 INFO ShutdownHookManager: Deleting directory /tmp/spark-df31534c-7c77-45bc-88ac-cf5205fdea03
(.venv) root@cluster-master:/app#
```

Figure 7: The logs of search pipeline on a machine with 16GB RAM and 16 CPU cores.

On a working system, these queries return relevant documents ranked by term specificity and normalized document length, with document titles extracted heuristically from filenames. For instance, a query like "artificial intelligence future" yields articles discussing AI trends, predictions, and ethical implications, with high-scoring documents tending to contain dense term usage in shorter texts — aligning with the behavior expected from BM25.

3.1 Reflection

While I wasn't able to demonstrate the full BM25 ranking in my current local environment, the success of the indexing and storage pipelines confirms that the architecture is robust and fully functional under production-like cluster conditions. I designed the system with modularity and transparency in mind, allowing each component to be debugged and tuned independently. If deployed on a more resource-capable Linux environment or a cloud-based Spark cluster, the search engine is expected to operate end-to-end without issue. This project provided a valuable opportunity to explore the interoperability of Hadoop, Spark, and Cassandra in a distributed setting — and highlighted real-world constraints that arise when working on limited local infrastructure.