CSci 4061: Introduction to Operating Systems
Fall 2020
Project #1: Basic Map Reduce

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Due: 5 pm, Oct. 7, 2020

1 Purpose

MapReduce [1, 2] is a programming model that allows processing on large datasets using two functions: `map` and `reduce`. It allows automatic parallelization of computation across multiple machines using multiple processes. Mapreduce model is widely used in industry for Big Data Analytics and is the de-facto standard for Big Data computing! In this project we will explore a simple verison of mapreduce using operating system primitives on a single machine which will use `fork`, `exec` and `wait` to run map and reduce functions. Utility functions that will help you with building the map and reduce tasks are provided with the project template. You will be given binaries for utilities that will run on the CSE-IT lab machines, we are **NOT** giving you source for the utilities since you may be asked to write them in future projects. You should work in groups of 3. `Please adhere to the output formats provided in each section.`

2 Problem Statement

The mapreduce programming model consist of two functions: map and reduce. The map function takes in <key, value> pairs, processes them and produces a set of intermediate <key, value> pairs. The key and value(s) are determined from input files. The intermediate pairs are then grouped based on the key. The reduce function will then reduce/merge the grouped intermediate values based on the key to produce the final result. Consider the following example map and reduce *logic* for counting the number of occurrences of each word in a large collection of documents.

Algorithm 1: `map`

Input: $(String\ \ key, String\ \ value)$, key: document name, value: document content
Result: $(w, count)$, where w is the word and $count$ is the number of occurrences of w in key

for *each word* w *in* $value$ **do**
  EmitIntermediate(w, 1) ;
end

Algorithm 2: `reduce`

Input: $(String\ \ key, Iterator\ \ values)$, key: a word, values: list of counts
Result: $result$, where result is the occurrence count of key

$result \leftarrow 0$;
for *each* v *in* $values$ **do**
  $result += v$;
end
return $(result)$;

In algorithm 1, the map function simply emits the count associated with a word. In algorithm 2, the reduce function sums together all the counts associated with the same word. **Note that the above algorithms are**

just a high level abstraction of the word count example. You will be seeing the detailed algorithms in sections 3.2 and 3.4.

In this project, we will design and implement a single machine map-reduce using system calls for the above word count application. There are four phases in this project: `Master, Map, Shuffle` and `Reduce`. In `Master` phase (Refer section 3.1), you will be provided with an input text file. The master will split the files in chunks of size 1024 bytes and share it uniformly with all the mapper processes. **Note: The division of input file into chunks and sharing it with the mappers are already present in the template code provided**. Once the mappers complete, the master will call the `Shuffle` phase to partition the files containing the grouped intermediate pairs for the reducers. **Note: the shuffle phase is already provided to you. You don't have to implement it**. Then your main program will spawn the reducer processes to carry out the final word count in the `Reduce` phase. In `Map` phase (Refer section 3.2), your mapper code will be provided with chunks of text data, each of size 1024 bytes. You will have to tokenize the text chunk using the utility function (`getWord`) provided and emit the `<word, "1">` pair into an `intermediate data structure`. Once the `Map` phase is complete, the contents of the `intermediate data structure` is written to `word.txt` files. In the `Shuffle` phase (Refer section 3.3), the generated `word.txt` files are partitioned across different reducers based on a `hash function`. Partitioning essentially allocates specific non-overlapping key ranges (i.e. words in our case) to specific reducers to share the load. Once the partitioning is complete, the `word.txt` file paths are shared with the `Reduce` phase. In the `Reduce` phase (Refer section 3.4), the reducers will read the `word.txt` files shared and compute the total word count corresponding to the word.

> **Objective:** You will have to design and implement the `Master, Map` and `Reduce` phase. The `Shuffle` phase will be provided to you as object code.

3 Phase Description

In this section, we will see the brief design details of different phases that will help you get started.

3.1 Phase 1: Master phase

The master process drives all the other phases in the project. It takes three inputs from the user: #mappers, #reducers and the path of the input text file relative to the provided Makefile location. The algorithm 3, provides a brief overview of the flow of control in the master process. This is your main control program. The code assumes the mapper and reducer executable are named `mapper` and `reducer`, though you can change this of course.

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File: src/mapreduce.c

Algorithm 3: `master:mapreduce`

Input: $(Integer\ nMappers, Integer\ nReducers, String\ inputFile)$, nMappers: #mappers, nReducers: #reducers, inputFile: text file to be processed

```
// directory creation and removal
bookeepingCode()*;
// sends 1024B chunks from inputFile to mappers
sendChunkData()*;

// spawn mapper processes with each calling exec on "mapper" executable
spawnMapper(nMappers);
// wait for all child processes to terminate
waitForAll();

// send token.txt files to reducers
shuffle()*;

// spawn nReducer processes with each calling exec on "reducer" executable
spawnReducers(nReducers);
// wait for all child processes to terminate
waitForAll();
```

Notice: *`bookeepingCode()`, `sendChunkData()` and `shuffle()` are defined in the provided utils.o object file. Please do not remove the function calls.

First, the master calls a `bookeepingCode()`, which takes care of the creation of `output`, `output/MapOut`, `output/ReduceOut`. Then it moves on to `sendChunkData()`, which divides the file into chunks of maximum size 1024B and stores them in a queue, from where the mappers will retrieve them one by one until there are no more. The mapper processes are spawned using `fork` which in turn calls `exec` family functions for executing the `mapper` executable. The master process will wait until all the mappers have completed their task. Then it moves to the `Shuffle` phase where the `word.txt` files are partitioned across the reducers. Following this, the master process will spawn the reducers which will call `exec` to execute the `reducer` executable. Again the master will wait for all the reducer processes to complete execution before exiting the code. Here is a picture!

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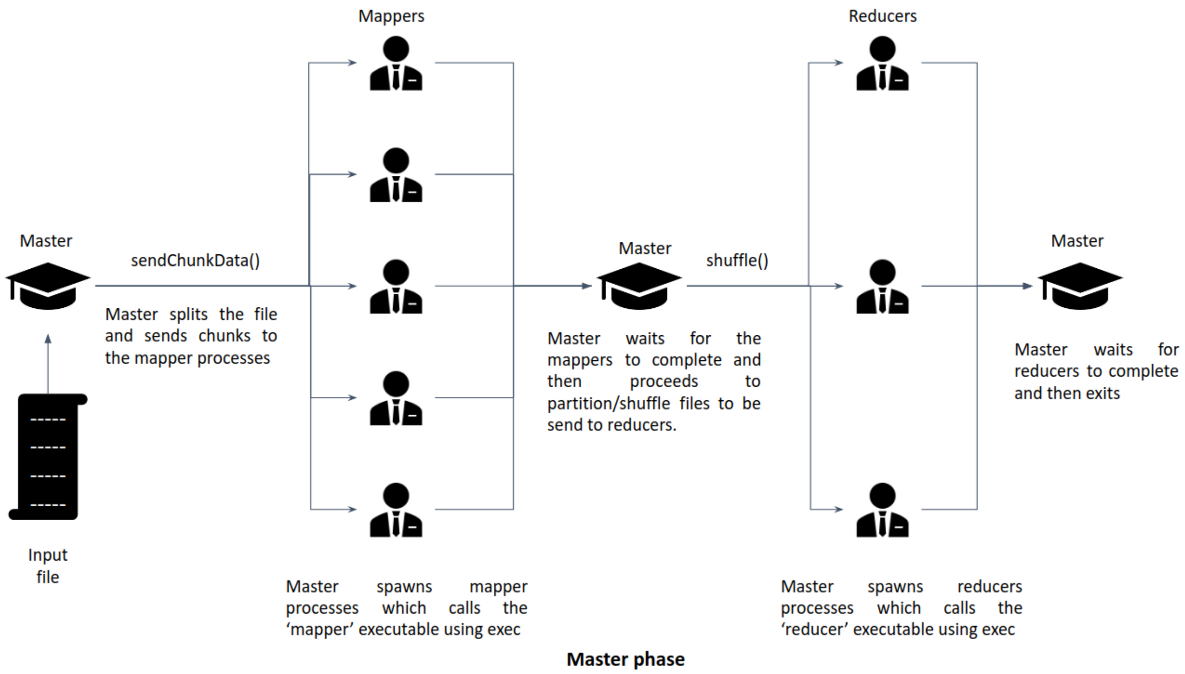


3.2 Phase 2: Map phase

The mapper takes in one input, the mapper's id (i.e. 1, 2, ...). This will be assigned by the master when it calls `exec` on the mapper executable (i.e. it must be passed to `exec` as a command-line argument). The flow of control in mapper is given in algorithm 4.
File: src/mapper.c

Algorithm 4: `mapper`

Input: $(Integer\ mapperID)$, mapperID: mapper's id assigned by master ∈ {1, 2, ..., nMappers}
Result: $(word.txt)$, text files containing the word and list of "1"s (word 1 1 1 1 ...)

// create mapper output directory
$mapOutDir \leftarrow createMapDir(mapperID)*$;

while *master send chunks* **do**
    $chunk \leftarrow getChunkData(mapperID)*$;
    $map(chunk)$;
end

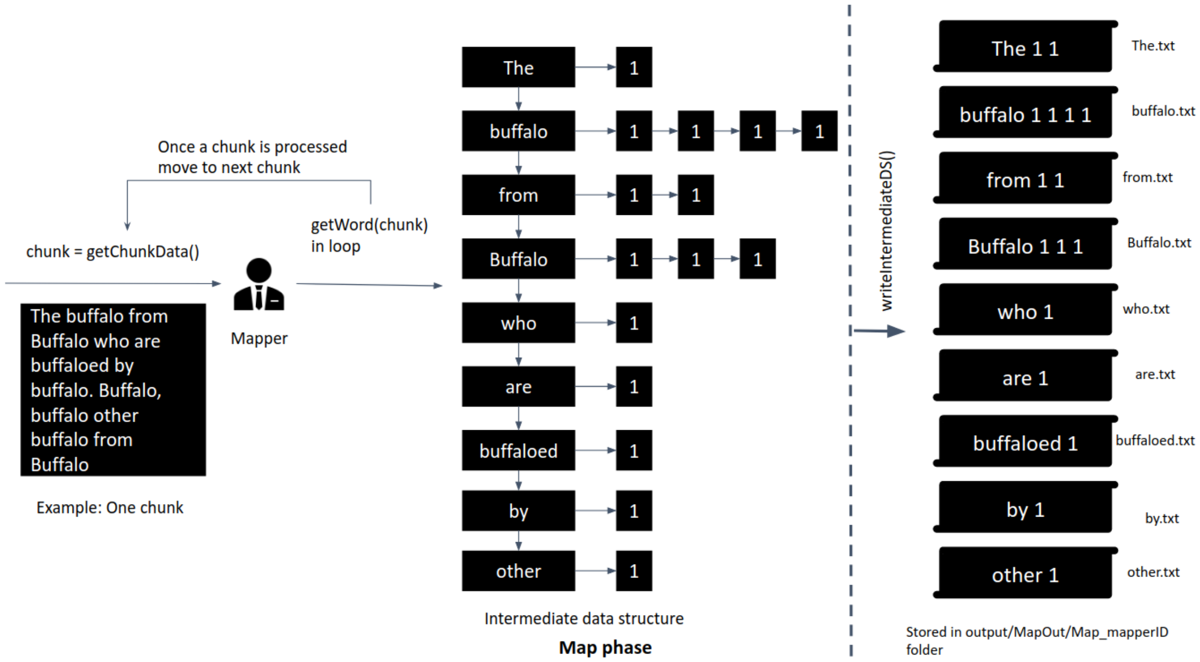
// write the intermediate structure contents to corresponding words.txt files
$writeIntermediateDS()$;

Notice: *`createMapDir()` and `getChunkData()` are defined in the provided utils.o object file. Please do not remove the function calls.

First, the mapper calls `createMapDir()` to create `output/MapOut/Map_mapperID` folder where the generated `word.txt` will be stored. In `Master` phase we saw that the master will be storing chunks of data into a queue. The mapper will use the `getChunkData()` to retrieve these chunks one by one (**Provided in code**). The received chunk is then passed to the `map()` to tokenize and to store the value "1" in an intermediate data structure. Note that a `word` can occur multiple times in a chunk, which means you will have to store a value list of "1"s associated with a `word`. The definition of `word` is given below:

Notice: A word should be composed of consecutive characters "c", where "c" ∈ {A...Z, a...z, 0...9}
Example: Thi's is. a te_xt* 0h gr8!!!
The words in this sentence are {Thi, s, is, a, te, xt, 0h, gr8}
Words are case sensitive, which means "text" and "Text" are different.
The `getWord()` utility allows you to extract out words from a chunk. Refer to `utils.h` for sample code.

A sample `intermediate data structure` you can use is provided in `mapper.h` along with the associated helper functions in `mapper.c`. It is a `two-level nested linked list`. The first level is used to store the word and the second level associated to each word is used to store "1"s. You are free to change the structure (A one level linked list with a large character array to store the "1"s can also be used). Once all the chunks are processed, the mapper will create a `word.txt` file associated with each word in the `intermediate structure`. The file content will look like "word 1 1 1 ...".



3.3 Phase 3: Shuffle phase

Notice: This phase is not meant to be implemented. It is already provided to you in the `mapreduce.c` file. Please do not remove the function call.

Once all the mapper processes complete and terminate, the master process will call the `shuffle()`. The shuffle function will divide the `word.txt` files in `output/MapOut/Map_mapperID` folders across nReducers and send the file paths to each reducer based on a hash function.

3.4 Phase 4: Reduce phase

The reducer takes in one input, the reducer's id. This will be assigned by the master when it calls the `exec` on the reducer executable similar to the mapper. The flow of control in the reducer is given in algorithm 5.

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File: src/reducer.c

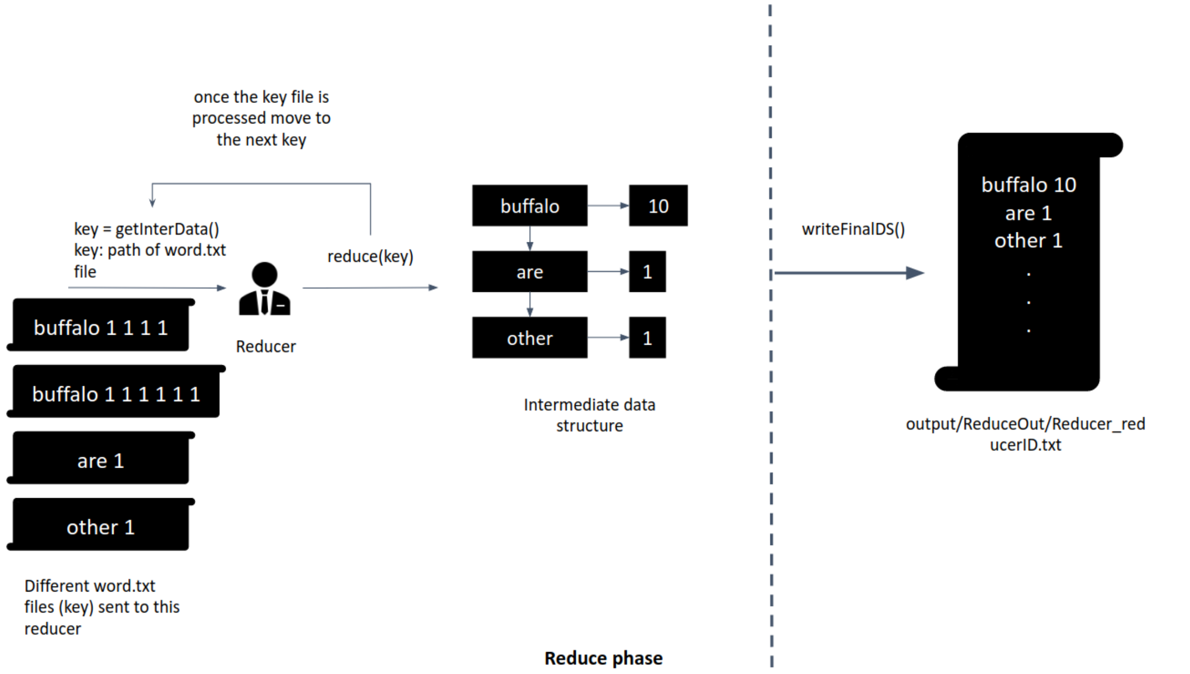
Algorithm 5: `reducer`

Input: $(Integer\ \ reducerID)$, reducerID: reducer's id assigned by master ∈ {1, 2, ..., nReducers}
Result: $Reducer\_reducerID.txt$, The text file will consist of the final count corresponding to each word sent to (i.e. assigned to) the reducer by the master

// character array to receive the word.txt path (i.e. the file containing the intermediate pairs for a particular key)
$var\quad key[KEYSZ]$;
while *master sends key* **do**
  $getInterData(key, reducerID)*$;
  $reduce(key)$;
end

// This is an optional function to write the final intermediate
// structure you may use to store the final <word, count> per reducer, to file Reduce_reducerID.txt
// Instead, you can add logic of your own to write the <word,count> data
// to Reduce_reducerID.txt in the reduce() function itself
$writeFinalDS()$;

Notice: *`getInterData()` is defined in the provided utils.o object file. Please do not remove the function call.



In the `Shuffle` phase, the master process will be sending the paths of `word.txt` to the reducers based on a hash function. This means files with same names across different `Map_mapperID` folders will be going to the same reducer. Once the reducer receives the file path which is the key, it passes it to the `reduce()`. The `reduce()` calculates the total count for the word from the file contents and stores it in an intermediate structure provided to you in `reducer.h` and `reducer.c`. The same process is repeated for all the `word.txt` files shared. Once all the files are processed, the reducer will then emit the "word count" results to a single file `Reduce_reducerID.txt`.

4 Compile and Execute

Compile

The current structure of the `Template` folder should be maintained. If you want to add extra source(.c) files, add it to `src` folder and for headers user `include`. The current `Makefile` should be sufficient to execute the code, but if you are adding extra files, modify the `Makefile` accordingly. For compiling the code, the following steps should be taken:

Command Line

```
$ cd Template
$ make
```

The template code will not error out on compiling.

Execute

Once the *make* is successful, run the mapreduce code with the required mapper count, reducer count and input file.

Command Line

```
$ ./mapreduce #mappers #reducers inputFile
```

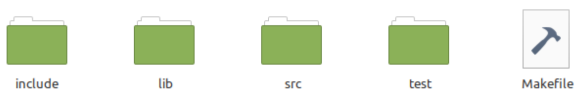
Notice: The final executable name should be `mapreduce`.

Note that number of mappers is greater than or equal to number of reducers. The inputFile path should be relative to the `Makefile` location.
On running the `mapreduce` executable without any modifications to template code will result in error.

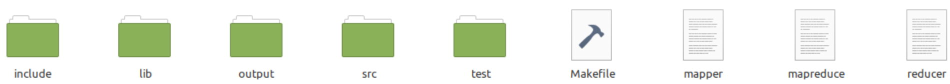
5 Expected Output

Please ensure to follow the guidelines listed below:

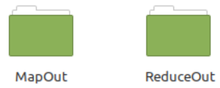
- Do not alter the folder structure. The structure should look as below before compiling via *make*:



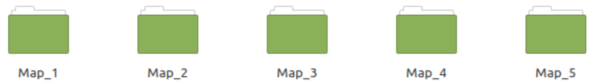
- After compilation, the folder structure will look as below. The output folder is auto-created:



- The output folder content (auto-created) will be as follows:



- The MapOut folder content (auto-created) will be as follows for 5 mappers:



- The Map_mapperID folder content will be as follows. The files should be created by your code:

- A sample word.txt file should look as follows. Here the list of "1"s emitted are from the value list associated with the `word` in the `intermediate structure` of `Map` phase. In this case, the word `above` occurred 8 times in the chunks retrieved by the corresponding mapper:

```
above 1 1 1 1 1 1 1 1
```

- The ReduceOut folder content will be as follows for 2 reducers. The files should be created by your code:

- A sample Reduce_reducerID.txt file should look as follows:

```
Periods 1
veil 8
raise 15
erspread 1
Exposed 1
Son 55
unmoved 7
righteous 5
anon 7
whence 30
```

6 Testing

A test folder is added to the template with one test case. You can run the testcase using the following command

Command Line

```
$ make t1
```

The working solution for the code is provided to you in the `solutionexe` folder. You can run navigate to the folder and run the following command to see the expected output. During the execution if there are any issues, please let us know as soon as possible.

Command Line

```
$ cd solutionexe
$ ./mapreduce #mappers #reducers test/T1/F1.txt
```

7 Assumptions / Points to Note

The following points should be kept in mind when you design and code:

- The input file sizes can vary, there is no limit.
- Number of mappers will be greater than or equal to number of reducers, other cases should error out.
- The system calls that will be used for the project are fork, exec and wait.
- Add error handling checks for all the system calls you use.
- Do not use the system call "system" to execute any command line executables.
- You can assume the maximum size of a file path to be 50 bytes.
- Follow the expected output information provided in the previous section.
- The chunk size will be atmost 1024 bytes as there is a chance that some of the 1024th byte in inputFile is the middle of a word.
- If you are using dynamic memory allocation in your code, ensure to free the memory after usage.
- **The provided lib/utils.o file will not run on Mac machines. ssh into Linux machines for using the object file.**

8 Deliverables

One student from each group should upload to Canvas , a zip file containing the source code, Makefile and a README that includes the following details:

- The purpose of your program
- How to compile the program
- What exactly your program does
- Any assumptions outside this document
- Team member names and x500
- Contribution by each member of the team

The README file does not have to be long, but mus properly describe the above points. The code should be well commented, it doesn't mean each and every line. When a TA looks at your code he/she/they should be able to understand the jist. You might want to focus on the "why" part, rather than the "how", when you add comments. At the top of the README file, please include the following:

README.md

```
test machine: CSELAB_machine_name
date: mm/dd/yy
name: full_name_1, [full_name_2, ...]
x500: id_first_name, [id_second_name, ...]
```

9 Getting started

Processes and exec
Start by experimenting with process creation, waiting and termination on simple code. Look at the man pages for `fork, wait`. Next create a simple hello world program, say `hello.c`. Create an executable `hello`. Now create another program called `driver.c`, that will be using different variants of `exec` calls to execute the `hello` executable.

File system calls
Use file system calls `open, write, read, close` to create a file, write some contents, read the contents and to close the file respectively. Note that there are multiple access control options associated with files. Have a look at the man pages of the function to understand them in detail. You can also use C library file calls like `fopen, fread, fwrite, fclose` or any other high-level I/O calls if you wish.

String manipulation
Since the project is about text data, visit various string manipulation functions available in `string.h`. Some of the important functions are `strcpy, strcat, strtok, strcmp, strtol`. Also have a look at `sprintf`.

Data structures and Dynamic memory allocation
The utility functions to manipulate the intermediate structures are already provided to you. But it would be good to have an understanding of pointers and memory allocation. So start with dynamic memory allocation for primitve types like char, int and then move to struct. Try out a simple linked list program whic inserts elements, traverses the list and free the memory allocated to the list.

10 Rubric: Subject to change

- 5% README
- 20% Documentation within code, coding, and style: indentations, readability of code, use of defined constants rather than numbers
- 75% Test cases: correctness, error handling, meeting the specifications
- Please make sure to pay attention to documentation and coding style. A perfectly working program will not receive full credit if it is undocumented and very difficult to read.
- A sample test case is provide to you upfront. You may change the value of #mappers and #reducers to test out your code. Think about other corner cases that may occur in the code, for example, an empty input file. Your code should be able to handle such cases. Please make sure that you read the specifications very carefully. If there is anything that is not clear to you, you should ask for a clarification.
- We will use the GCC version installed on the CSELabs machines(i.e. 9.3.0) to compile your code. Make sure your code compiles and run on CSELabs.
- **Please make sure that your program works on the CSELabs machines** e.g., KH 4-250 (csel-kh4250-xx.cselabs.umn.edu). You will be graded on one of these machines.

11 Testing strategy

We will be comparing the results of your `map/MapOut/Map_mapperID` and `map/ReduceOut/Reduce_reducerID.txt` with the one that we have generated. The TAs will be going through your code to see if system calls are used correctly. Error handling is a must for all the system calls. Ensure that the total number of processes created by the master is #mappers + #reducers, without including the ones generated by the template code. Proper creation of intermediate data structure along with freeing the memory after usage will be checked.

References

[1] Dean, J., & Ghemawat, S. (2008). MapReduce: simplified data processing on large clusters. Communications of the ACM, 51(1), 107-113.

[2] Dean, J., & Ghemawat, S. (2004). MapReduce: Simplified data processing on large clusters.