CS 425 / ECE 428
Distributed Systems
Fall 2025

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Lecture 4: Mapreduce and Hadoop

Announcements

- **Please fill out Student Survey (see course webpage).**
- DO NOT
  - Change MP groups unless your partner has dropped
  - Leave your MP partner hanging: Both MP partners should contribute equally (we will ask!)

- **MP1 due Sep 14th**
  - **VMs distributed soon (watch Piazza)**
  - **Demos will be Monday Sep 15th** (schedule and details will be posted next week on Piazza)
- HW1 due Sep 18th Thu 2 pm : Solve problems right after lecture covers topic!
- Check Piazza often! It's where all the announcements are at!

- (deadline passed) **MP Groups Form DUE this week Mon Sep 1st** @ 5 pm (see course webpage).

What is MapReduce?

- Terms are borrowed from Functional Language (e.g., Lisp)

Sum of squares:

- (map square ‘(1 2 3 4))
  - Output: (1 4 9 16)

  [processes each record sequentially and independently]

- (reduce + ‘(1 4 9 16))
  - (+ 16 (+ 9 (+ 4 1)))
  - Output: 30

  [processes set of all records in batches]

- Let’s consider a sample application: Wordcount
  - You are given a <u>huge</u> dataset (e.g., Wikipedia dump or all of Shakespeare’s works) and asked to list the count for each of the words in each of the documents therein

Map

- Process individual records to generate intermediate key/value pairs.

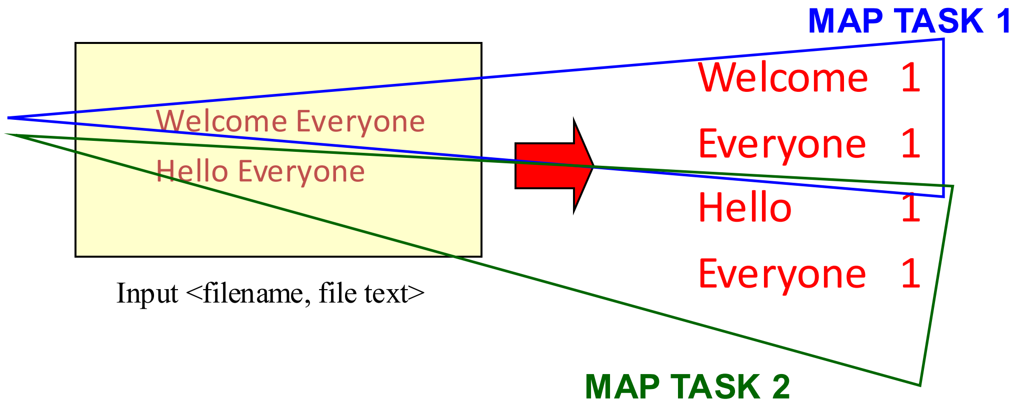
Welcome Everyone
Hello Everyone

Input <filename, file text>

Key	Value
Welcome	1
Everyone	1
Hello	1
Everyone	1

Map

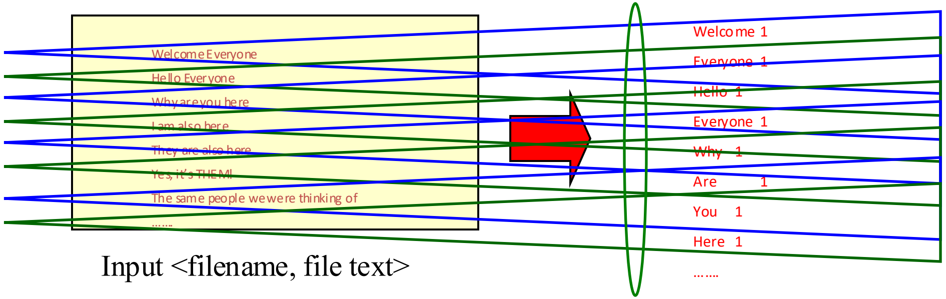
- Parallelly Process individual records to generate intermediate key/value pairs.



Input <filename, file text>

Map

- Parallelly Process a large number of individual records to generate intermediate key/value pairs.



MAP TASKS

Reduce

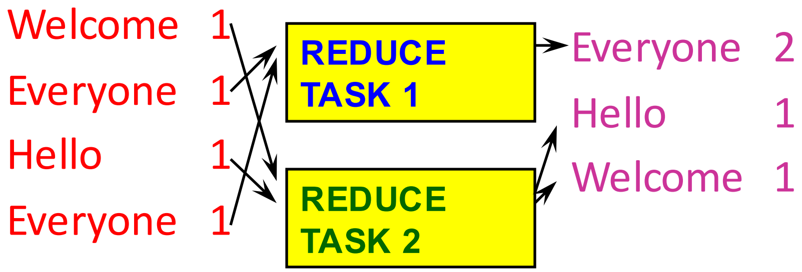
- Reduce processes and merges all intermediate values associated per key

Welcome	1
Everyone	1
Hello	1
Everyone	1

Key	Value
Everyone	2
Hello	1
Welcome	1

Reduce

- Each key assigned to one Reduce
- Parallelly Processes and merges all intermediate values by partitioning keys



- Popular: *Hash partitioning, i.e.,* key is assigned to
  - reduce # = hash(key)%number of reduce tasks

Hadoop Code - Map

```
public static class MapClass extends MapReduceBase    implements
Mapper<LongWritable, Text, Text, IntWritable> {
  private final static IntWritable one =
    new IntWritable(1);
  private Text word = new Text();

  public void map( LongWritable key, Text value,
      OutputCollector<Text, IntWritable> output, Reporter reporter)
                        // key is empty, value is the line
    throws IOException {
    String line = value.toString();
    StringTokenizer itr = new StringTokenizer(line);
    while (itr.hasMoreTokens()) {
     word.set(itr.nextToken());
     output.collect(word, one);
    }
  }
} // Source: http://developer.yahoo.com/hadoop/tutorial/module4.html#wordcount
```

Hadoop Code - Reduce

```
public static class ReduceClass extends MapReduceBase implements
Reducer<Text, IntWritable, Text, IntWritable> {
  public void reduce(
      Text key,
      Iterator<IntWritable> values,
      OutputCollector<Text, IntWritable> output,
      Reporter reporter)
     throws IOException {
           // key is word, values is a list of 1's
           // called exactly once for each key (e.g., "hello")
      int sum = 0;
      while (values.hasNext()) {
        sum += values.next().get();
      }
      output.collect(key, new IntWritable(sum));
  }
}
```

Hadoop Code - Driver

```
// Tells Hadoop how to run your Map-Reduce job
public void run (String inputPath, String outputPath)
      throws Exception {
  // The job. WordCount contains MapClass and Reduce.
  JobConf conf = new JobConf(WordCount.class);
  conf.setJobName(”mywordcount");
  // The keys are words
  (strings) conf.setOutputKeyClass(Text.class);
  // The values are counts (ints)
  conf.setOutputValueClass(IntWritable.class);
  conf.setMapperClass(MapClass.class);
  conf.setReducerClass(ReduceClass.class);
  FileInputFormat.addInputPath(
      conf, newPath(inputPath));
  FileOutputFormat.setOutputPath(
      conf, new Path(outputPath));
  JobClient.runJob(conf);
}
```
// Source: http://developer.yahoo.com/hadoop/tutorial/module4.html#wordcount

Some Applications of MapReduce

Distributed Grep:

- Input: large set of files
- Output: lines that match pattern

- Map – *Emits a line if it matches the supplied pattern*
- Reduce – *Copies the intermediate data to output*

Some Applications of MapReduce (2)

Reverse Web-Link Graph

- Input: Web graph: tuples (a, b) where (page a → page b)
- Output: For each page, list of pages that link *to* it

- Map – *process web log and for each input <source, target>, it outputs <target, source>*
- Reduce - *emits <target, list(source)>*

Some Applications of MapReduce (3)

Count of URL access frequency

- Input: Log of accessed URLs, e.g., from proxy server
- Output: For each URL, % of total accesses for that URL

- Map – *Process web log and outputs <URL, 1>*
- Multiple Reducers - *Emits <URL, URL_count>*

(So far, like Wordcount. But still need %)

- Chain another MapReduce job after above one
- Map – *Processes <URL, URL_count>* and outputs *<1, (<URL, URL_count>)>*
- 1 Reducer – Does two passes. In first pass, sums up all *URL_count's* to calculate overall_count. In second pass calculates %'s

Emits multiple <URL, URL_count/overall_count>

Some Applications of MapReduce (4)

Map task's output is sorted (e.g., quicksort)
Reduce task's input is sorted (e.g., mergesort)

Sort

- Input: Series of (key, value) pairs
- Output: Sorted <value>s

- Map – *<key, value>* → *<value, _>* *(identity)*
- Reducer – *<key, value>* → *<key, value>* *(identity)*
- Partitioning function – partition keys across reducers based on **ranges** (can't use hashing!)
  - Take data distribution into account to balance reducer tasks

Programming MapReduce

Externally: For user

1. Write a Map program (short), write a Reduce program (short)
2. Specify number of Maps and Reduces (parallelism level)
3. Submit job; wait for result
4. Need to know very little about parallel/distributed programming!

Internally: For the Paradigm and Scheduler

1. Parallelize Map
2. Transfer data from Map to Reduce (**shuffle data**)
3. Parallelize Reduce
4. Implement Storage for Map input, Map output, Reduce input, and Reduce output

(Ensure that no Reduce starts before all Maps are finished. That is, ensure the ***barrier*** between the Map phase and Reduce phase)

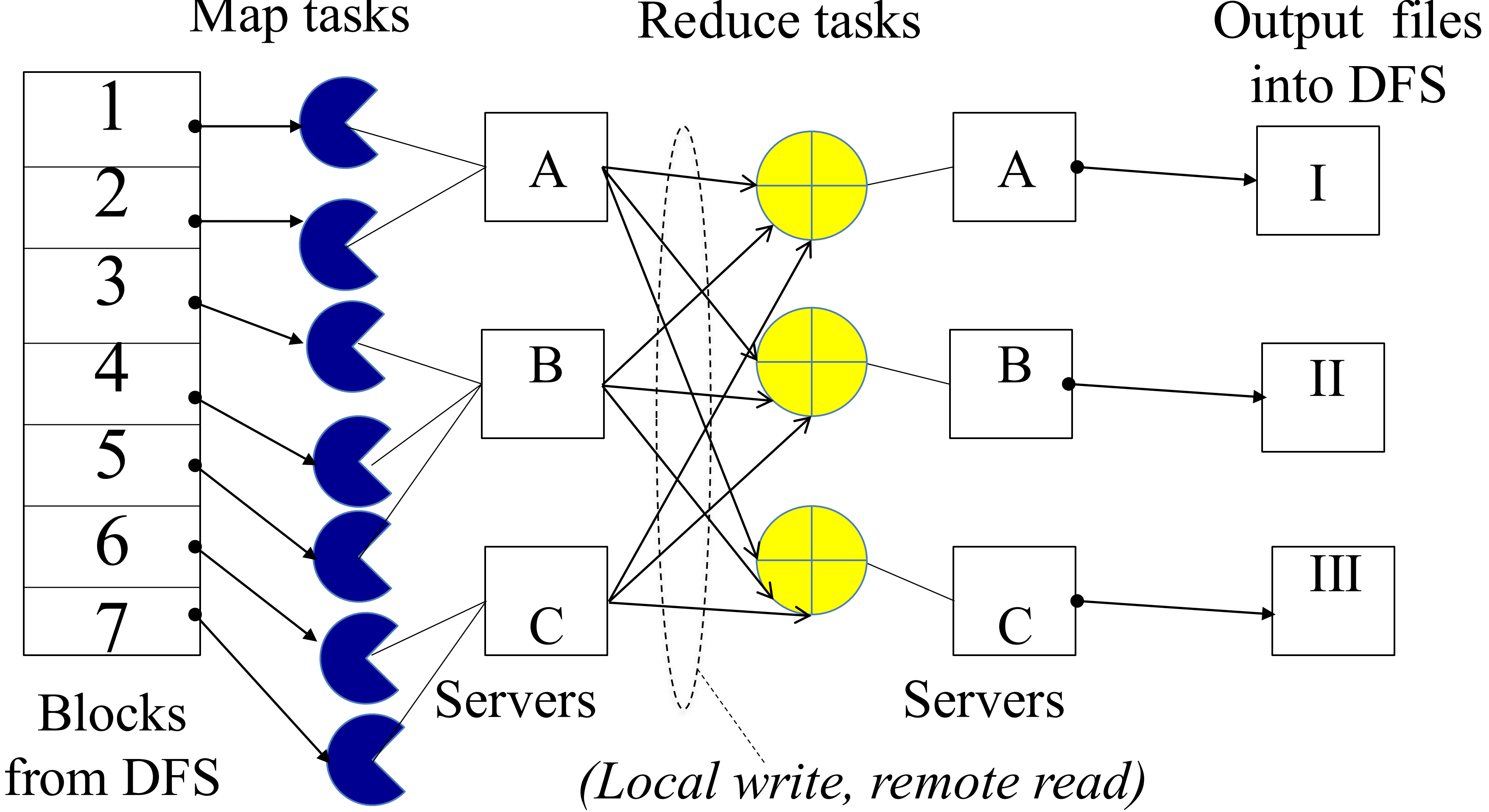
Inside MapReduce

For the cloud:

1. Parallelize Map: easy! each map task is independent of the other!
   - All Map output records with same key assigned to same Reduce
2. Transfer data from Map to Reduce:
   - Called Shuffle data
   - All Map output records with same key assigned to same Reduce task
   - use partitioning function, e.g., hash(key)%number of reducers
3. Parallelize Reduce: easy! each reduce task is independent of the other!
4. Implement Storage for Map input, Map output, Reduce input, and Reduce output
   - Map input: from distributed file system
   - Map output: to local disk (at Map node); uses local file system
   - Reduce input: from (multiple) remote disks; uses local file systems
   - Reduce output: to distributed file system

local file system = Linux FS, etc.

distributed file system = GFS (Google File System), HDFS (Hadoop Distributed File System)

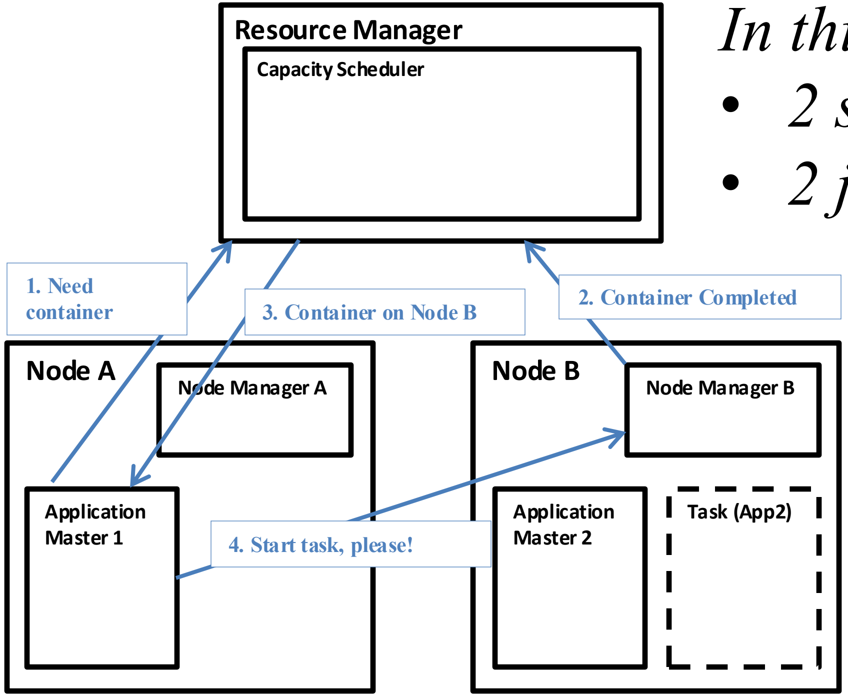


Resource Manager (assigns maps and reduces to servers)

The YARN Scheduler

- Used underneath Hadoop 2.x +
- YARN = Yet Another Resource Negotiator
- Treats each server as a collection of *containers*
  - Container = fixed CPU + fixed memory (think of Linux cgroups, but even more lightweight)
- Has 3 main components
  - Global *Resource Manager (RM)*
    - Scheduling
  - Per-server *Node Manager (NM)*
    - Daemon and server-specific functions
  - Per-application (job) *Application Master (AM)*
    - Container negotiation with RM and NMs
    - Detecting task failures of that job

YARN: How a job gets a container



In this figure

- *2 servers (A, B)*
- *2 jobs (1, 2)*

Fault Tolerance

- Server Failure
  - NM heartbeats to RM
    - If server fails: RM times out waiting for next heartbeat, RM lets all affected AMs know, and AMs take appropriate action
  - NM keeps track of each task running at its server
    - If task fails while in-progress, mark the task as idle and restart it
  - AM heartbeats to RM
    - On failure, RM restarts AM, which then syncs it up with its running tasks
- RM Failure
  - Use old checkpoints and bring up secondary RM
- Heartbeats also used to piggyback container requests
  - Avoids extra messages

Slow Servers

Slow tasks are called Stragglers

- The slowest task slows the entire job down (why?)
- Due to Bad Disk, Network Bandwidth, CPU, or Memory
- Keep track of "progress" of each task (% done)
- Perform proactive backup (replicated) execution of some straggler tasks
  - A task considered done when its first replica complete (other replicas can then be killed)
  - Approach called Speculative Execution.

Barrier at the end of Map phase!

Locality

- Locality
  - Since cloud has hierarchical topology (e.g., racks)
  - For server-fault-tolerance, GFS/HDFS stores 3 replicas of each of the chunks (e.g., 64 MB in size)
    - For rack-fault-tolerance, on different racks, e.g., 2 on a rack, 1 on a different rack
  - Mapreduce attempts to schedule a map task on
    1. a machine that contains a replica of corresponding input data, or failing that,
    2. on the same rack as a machine containing the input, or failing that,
    3. Anywhere
  - Note: The 2-1 split of replicas is intended to reduce bandwidth when writing file.
    - Using more racks does not affect overall Mapreduce scheduling performance

That was Hadoop 2.x…

- Hadoop 3.x (new!) over Hadoop 2.x
  - Dockers instead of container
  - Erasure coding instead of 3-way replication
  - Multiple Namenodes instead of one (name resolution)
  - GPU support (for machine learning)
  - Intra-node disk balancing (for repurposed disks)
  - Intra-queue preemption in addition to inter-queue
  - *(From https://hortonworks.com/blog/hadoop-3-adds-value-hadoop-2/ (broken) and https://hadoop.apache.org/docs/r3.0.0/)*

Mapreduce: Summary

- Mapreduce uses parallelization + aggregation to schedule applications across clusters
- Need to deal with failure
- Plenty of ongoing research work in scheduling and fault-tolerance for Mapreduce and Hadoop

Further MapReduce Exercises

Exercise 1

1. (MapReduce) You are given a symmetric social network (like Facebook) where a is a friend of b implies that b is also a friend of a. The input is a dataset D (sharded) containing such pairs (a, b) – note that either a or b may be a lexicographically lower name. Pairs appear exactly once and are not repeated. **Find the last names of those users whose first name is "Ye" and who have at least 300 friends. You can assum full names are unique.** You can chain Mapreduces if you want (but only if you must, and even then, only the least number). You don't need to write code – pseudocode is fine as long as it is understandable. Your pseudocode may assume the presence of appropriate primitives (e.g., "firstname(user_id)", etc.). The Map function takes as input a tuple (key=a,value=b).

Exercise 1: Solution

***Goal**: Last names of those users whose first name is "*Ye*" and who have at least 300 friends.*

- M1 (a,b):
  - if (firstname(a)==Ye) then output (a,b)
  - if (firstname(b)== Ye) then output (b,a)
    - // note that second if is NOT an else if, so a single M1 function may be output up to 2 KV pairs!
- R1 (x, V):
  - if |V| >= 300 then output (lastname(x), -)

Exercise 2

2. For an asymmetrical social network, you are given a dataset D where lines consist of (a,b) which means user a follows user b. **Write a MapReduce program (Map and Reduce separately) that outputs the list of all users U who satisfy the following three conditions simultaneously**: i) user U has at least 2 million followers, and ii) U follows fewer than 20 other users, and iii) all the users that U follows, also follow U back.

Exercise 2: Solution

***Goal**: Find users U*

i) U has >= 2 million followers

ii) U follows < 20 other users,

iii) all U's followers follow U back

- M1(a,b):
  - Output (key=a, value=(OUT,b))
  - Output (key=b, value=(IN,a))
    - // Note that a single M1 function outputs exactly TWO KV pairs

- R1(key=x, V):
  - Collect Sout = set of all (OUT,*) value items from V
  - Collect Sin = set of all (IN,*) value items from V
  - if (|Sout| < 20 AND |Sin| >= 2M AND all items in Sout are also present in Sin) // third term via nested for loops
    - then output (x,_)

Exercise 3

3. For an asymmetrical social network, you are given a dataset D where lines consist of (a,b) which means user a follows user b. Write a MapReduce program (Map and Reduce separately) that outputs the **list of all user *pairs* (x,y) who satisfy the following three conditions simultaneously**: i) x has fewer than 100 M followers, ii) y has fewer than 100M followers, iii) x and y follow each other, and iv) *the sum* of x's followers and y's followers (double-counting common followers that follow both x and y is ok) is 100 M or more. Your output should not contain duplicates (i.e., no (x,y) and (y,x)).

Exercise 3: Solution

***Goal**: find pairs (x,y):*

i) x has < 100 M followers,

ii) y has < 100M followers,

iii) x and y follow each other,

iv) sum of x's & y's followers >= 100 M (double count ok).

- M1(a,b): output (b,a)
- R1(x,V):
  - if |V| < 100M, then for all a in V, output (lexicographic_sorted_pair(x,a), |V|)
- M2(a,b): Identity
- R2(key=(a,b), value={|V1|, |V2|,…})
  - if |value|==1 output nothing // they don't follow each other
  - else if |value|==2 then add value entries // follow each other
    - if sum of value entries >= 100M then output (a,b)

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