Traditional programming is serial

Parallel programming

- Split processing into parts that can be executed concurrently on multiple processors

Challenge

- Identify tasks that can run concurrently and/or groups of data that can be processed concurrently
- Not all problems can be parallelized
Parallel programming is hard

Interact with the distributed environment

– Split up data
– Allocate servers
– Get programs onto those servers and start them
– Partition the work among the processes
– Monitor for failure
– Restart failed processes
– Collect the results
Simplest environment for parallel processing

• No dependency among data
• Data can be split into lots of smaller chunks - shards
• Each process can work on a chunk
• Master/worker approach

**Master**
- Initializes data set and splits it according to # of workers
- Sends each worker a sub-array of data
- Receives the results from each worker

**Worker**
- Receives a sub-array from master
- Performs processing
- Sends results to master
MapReduce

Created by Google in 2004
Jeffrey Dean and Sanjay Ghemawat

Inspired by LISP

Map(function, set of values)
- Applies function to each value in the set
  \[(\text{map } \text{`length }\text{` }(((\text{a} \quad \text{b} \quad \text{c}))) \Rightarrow (0 \quad 1 \quad 2 \quad 3)\]

Reduce(function, set of values)
- Combines all the values using a binary function (e.g., +)
  \[(\text{reduce } \text{`}+\text{` }((1 \quad 2 \quad 3 \quad 4 \quad 5)) \Rightarrow 15)\]
MapReduce

- Framework for parallel computing
- Programmers get simple API
- Don’t have to worry about handling
  - Parallelization
  - Data distribution
  - Load balancing
  - Fault tolerance

Allows a user to process huge amounts of data (terabytes and petabytes) on thousands of processors
Who has it?

• Google
  – Original proprietary implementation
  – Runs on the same computers as the data storage (GFS, Bigtable)

• Apache Hadoop MapReduce
  – Most common (open-source) implementation
  – Built to specs defined by Google

• Others
  – Amazon Elastic MapReduce – uses Hadoop MapReduce running on Amazon EC2
  – Microsoft Azure HDInsight
  – Google Cloud MapReduce for App Engine
MapReduce

Map:
- Grab the relevant data from the source
- User function gets called for each chunk of input
- Spits out (key, value) pairs

Reduce:
- Aggregate the results
- User function gets called for each unique key with all values corresponding to that key
MapReduce

**Map:** (input shard) → intermediate(key/value pairs)
- Automatically partition input data into $M$ shards
- Discard unnecessary data and generate (key, value) sets
- Framework groups together all intermediate values with the same intermediate key & pass them to the *Reduce* function

**Reduce:** intermediate(key/value pairs) → result files
- Input: key & set of values
- Merge these values together to form a smaller set of values

Reduce workers are distributed by partitioning the intermediate key space into $R$ pieces using a partitioning function (default = $hash(key) \mod R$)
- The user specifies the # of partitions ($R$) and the partitioning function
MapReduce: what happens in between?

• Map
  – Grab the relevant data from the source (parse into key, value)
  – Write it to an intermediate file

• Partition
  – Partitioning: identify which of R reducers will handle which keys
  – Map partitions data to target it to one of R Reduce workers based on a partitioning function (both R and partitioning function user defined)

• Shuffle & Sort
  – Shuffle: Fetch the relevant partition of the output from all mappers
  – Sort by keys (different mappers may have sent data with the same key)

• Reduce
  – Input is the sorted output of mappers
  – Call the user Reduce function per key with the list of values for that key to aggregate the results
Step 1: Split input files into chunks (shards)

Break up the input data into $M$ pieces (typically 64 MB)

Input files

Divided into $M$ shards
Step 2: Fork processes

- Start up many copies of the program on a cluster of machines
  - **One master**: scheduler & coordinator
  - Lots of workers

- Idle workers are assigned either:
  - **map tasks** (each works on a shard) – there are $M$ map tasks
  - **reduce tasks** (each works on intermediate files) – there are $R$ tasks
    - $R = \#$ partitions, defined by the user
Step 3: Run Map Tasks

- Reads contents of the input shard assigned to it
- Parses key/value pairs out of the input data
- Passes each pair to a user-defined map function
  - Produces intermediate key/value pairs
  - These are buffered in memory
Step 4: Create intermediate files

- Intermediate key/value pairs produced by the user’s map function buffered in memory and are periodically written to the local disk
  - Partitioned into $R$ regions by a partitioning function

- Notifies master when complete
  - Passes locations of intermediate data to the master
  - Master forwards these locations to the reduce worker
Step 4a. Partitioning

- Map data will be processed by Reduce workers
  - User’s Reduce function will be called once per unique key generated by Map.

- We first need to group all the (key, value) data by keys and decide which Reduce worker processes which keys
  - The Reduce worker will later sort the values within the keys

- Partition function
  Decides which of R reduce workers will work on which key
  - Default function: \( \text{hash(key)} \ mod \ R \)
  - Map worker partitions the data by keys

- Each Reduce worker will later read their partition from every Map worker
Step 5: Reduce Task: Shuffle & Sort

- Reduce worker is notified by master about the location of intermediate files for its partition.
- **Shuffle**: Uses RPCs to read the data from the local disks of the map workers.
- **Sort**: When the *reduce* worker gets all the *(key, value)* data for its partition from all workers:
  - It sorts the data by the intermediate keys.
  - All occurrences of the same key are grouped together.

![Diagram showing the process of shuffle and sort]

*Map worker → Intermediate file → Reduce worker → Map worker → Intermediate file → Reduce worker*
Step 6: Reduce Task: Reduce

- The sort phase grouped data by keys
- User’s Reduce function is given the key and the set of intermediate values for that key
  \[ <key, (value1, value2, value3, value4, \ldots)> \]
- The output of the Reduce function is appended to an output file
Step 7: Return to user

• When all map and reduce tasks have completed, the master wakes up the user program.

• The MapReduce call in the user program returns and the program can resume execution.

• Output of MapReduce is available in R output files.
Example: Word Count

• Count # occurrences of each word in a collection of documents

• Map:
  – Parse data; output each word and a count (1)

• Reduce:
  – Sort: sort by keys (words)
  – Reduce: Sum together counts each key (word)

```java
map(String key, String value):
  // key: document name, value: document contents
  for each word w in value:
    EmitIntermediate(w, "1");

reduce(String key, Iterator values):
  // key: a word; values: a list of counts
  int result = 0;
  for each v in values:
    result += ParseInt(v);
  Emit(AsString(result));
```
Example: Word Count

Input

It will be seen that this mere painstaking burrower and grub-worm of a poor devil of a Sub-Sub appears to have gone through the long Vaticans and street-stalls of the earth, picking up whatever random allusions to whales he could anyways find in any book whatsoever, sacred or profane. Therefore you must not, in every case at least, take the higgledy-piggledy whale statements, however authentic, in these extracts, for veritable gospel cetology. Far from it. As touching the ancient authors ...

After Map

Input to reduce()

Output from reduce()
Fault tolerance

Master pings each worker periodically

• If no response is received within a certain time, the worker is marked as *failed*

• *Map* or *reduce* tasks given to this worker are reset back to the initial state and rescheduled for other workers
• **Input and Output data comes from:**
  – GFS (Google File System) file or files
  – Bigtable, Spanner

• **MapReduce (often) runs on GFS chunkservers**
  – Keep computation close to the files if possible

• **Master tries to schedule map worker on one of the machines that has a copy of the input chunk it needs**
Other Examples: Search

Distributed grep (search for words)

- Search for words in lots of documents
- Map: emit a line if it matches a given pattern
- Reduce: just copy the intermediate data to the output

**Map**

Input: line of text
If pattern matches
Output: ", line"

**Reduce**

Input: ", [lines]
Output: lines
List URL access counts

- *Find the count of each URL in web logs*
- Map: process logs of web page access; output `<URL, 1>`
- Reduce: add all values for the same URL

**Map**
- Input: line from log
- Output: `(url, 1)`

**Reduce**
- Input: `url, [accesses]`
- Output: `url, sum(accesses)`
Count URL access frequency

- *Find the frequency of each URL in web logs*
- Run 1: just count total URLs
- Run 2: just like URL count but now we stored $\text{total_urls}$

**Run 1**

**Map**

Input: line from log  
Output: ("", 1)

**Reduce**

Input: "", [1, 1, ..., 1]  
Output: $\text{total_urls} = \text{sum}(1, 1, ..., 1)$

**Run 2**

**Map**

Input: line from log  
Output: (url, 1)

**Reduce**

Input: url, [accesses]  
Output: url, $\text{sum(accesses)}/\text{total_urls}$
Other Examples

Reverse web-link graph

- Find where page links come from
- Map: output <target, source> for each link to target in a page source
- Reduce: concatenate the list of all source URLs associated with a target

Output <target, list(source)>

Map

Input: HTML files
Output: (target, source)

Reduce

Input: target, [sources]
Output: target, [sources]

The reduce function does nothing – it just writes the input to the output!
Other Examples

Inverted index

- *Find what documents contain a specific word*
- Map: parse document, emit `<word, document-ID>` pairs
- Reduce: for each word, sort the corresponding document IDs
  Emit a `<word, list(document-ID)>` pair
The set of all output pairs is an inverted index
Other Examples

Stock performance summary

- Find average daily gain of each company from 1/1/2010 – 12/31/2020
- Data is a set of lines: { date, company, start_price, end_price }

Map

If (date >= "1/1/2010" && date <= "12/31/2020")
   Output: (company, end_price - start_price)

Reduce

Input: company, [daily_gains]
Output: word, average([daily_gains])
Other Examples: Two rounds of MapReduce

**Average salaries in regions**

- **Show zip codes where average salaries are in the ranges:**
  1. $<$ $100K
  2. $100K$ … $500K$
  3. $>$ $500K$

- Data is a set of lines: \{ name, age, address, zip, salary \}

**Map**

Output: (zip, salary)

**Reduce**

Input: zip, [salary]
Output: zip, average([salary])

Show average salary for each zip code

**Map(zip, salary)**

if (salary < 100K)
output("<$100K", zip)
else if (salary > 500K)
output(">$500K", zip)
else
output("$100-500K", zip)

**Reduce**

Input: range, [zips]
Output: range
For z in zips
output(z)
MapReduce for Rendering Map Tiles

<table>
<thead>
<tr>
<th>Input</th>
<th>Map</th>
<th>Shuffle</th>
<th>Reduce</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic feature list</td>
<td>Emit each to all overlapping latitude-longitude rectangles</td>
<td>Sort by key (key= Rect. Id)</td>
<td>Render tile using data for all enclosed features</td>
<td>Rendered tiles</td>
</tr>
</tbody>
</table>

From Designs, Lessons and Advice from Building Large Distributed Systems
Jeff Dean, Google
Used with permission
MapReduce Summary

• Get a lot of data

• Map
  – Parse & extract items of interest

• Sort (shuffle) & partition

• Reduce
  – Aggregate results

• Write to output files
All is not perfect

• MapReduce was used to process webpage data collected by Google's crawlers.
  – It would extract the links and metadata needed to search the pages
  – Determine the site's PageRank

• The process took around eight hours!
  – Results were moved to search servers
  – This was done continuously
All is not perfect

• Web has become more dynamic
  – An 8+ hour delay is a lot for some sites
  – Goal: refresh certain pages within seconds

• MapReduce
  – Batch-oriented
  – Not suited for near-real-time processes
  – Cannot start a new phase until the previous has completed
    • Reduce cannot start until all Map workers have completed
  – Suffers from “stragglers” – workers that take too long (or fail)
    – This was done continuously

• MapReduce is still useful but there are also other options

• Search framework updated in 2009-2010: Caffeine
  – Analyze web in small portions
  – Update index by making direct changes to data stored in Bigtable
  – Process hundreds of thousands of pages per second in parallel – data resides in Colossus (GFS2) instead of GFS
In Practice

• Most data not simple files
  – B-trees, tables, SQL databases, memory-mapped key-values

• Hardly ever use textual data: slow & hard to parse
  – Most I/O encoded with Protocol Buffers
More info

• Good tutorial presentation & examples at:
  http://research.google.com/pubs/pub36249.html

• The definitive paper:
  http://labs.google.com/papers/mapreduce.html
The End