

# Map-Reduce and the New Software Stack

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Mining of Massive Datasets

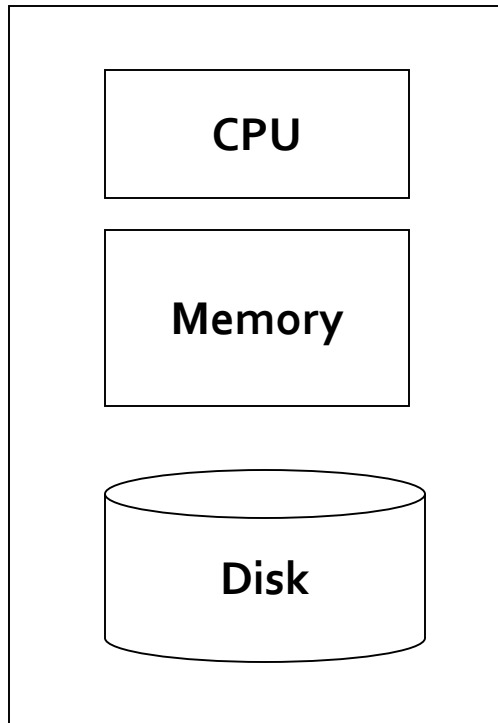
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# MapReduce

- Much of the course will be devoted to **large scale computing for data mining**
- **Challenges:**
  - How to distribute computation?
  - Distributed/parallel programming is hard
- **Map-reduce** addresses all of the above
  - Google's computational/data manipulation model
  - Elegant way to work with big data

# Single Node Architecture



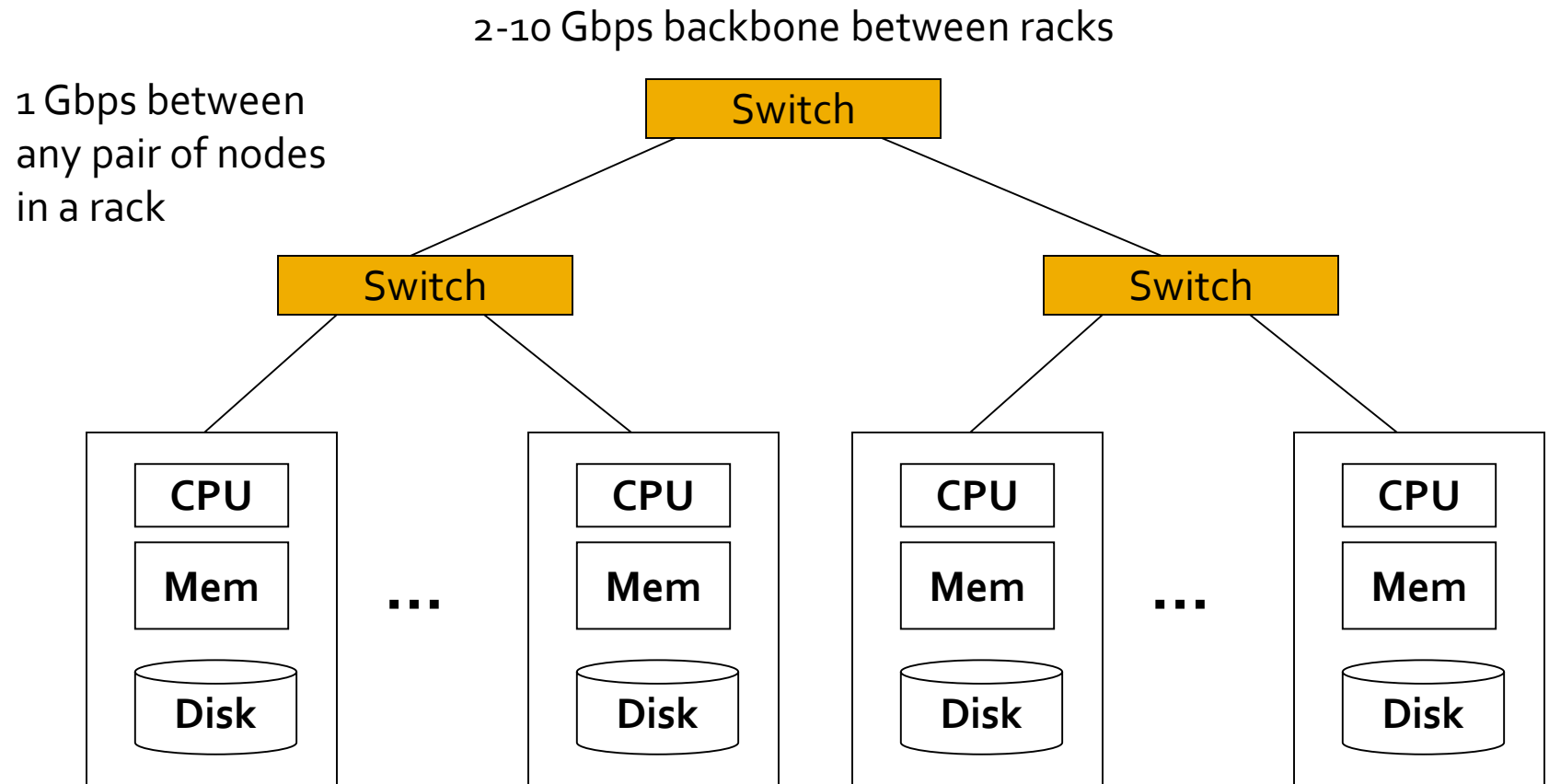
**Machine Learning, Statistics**

**“Classical” Data Mining**

# Motivation: Google Example

- 20+ billion web pages x 20KB = 400+ TB
- 1 computer reads 30-35 MB/sec from disk
  - ~4 months to read the web
- ~1,000 hard drives to store the web
- Takes even more to **do something useful with the data!**
- **Today, a standard architecture for such problems is emerging:**
  - Cluster of commodity Linux nodes
  - Commodity network (ethernet) to connect them

# Cluster Architecture



Each rack contains 16-64 nodes

In 2011 it was guestimated that Google had 1M machines, <http://bit.ly/Shh0RO>



# Large-scale Computing

- **Large-scale computing for data mining problems on commodity hardware**
- **Challenges:**
  - **How do you distribute computation?**
  - **How can we make it easy to write distributed programs?**
  - **Machines fail:**
    - One server may stay up 3 years (1,000 days)
    - If you have 1,000 servers, expect to loose 1/day
    - People estimated Google had ~1M machines in 2011
      - 1,000 machines fail every day!



# Idea and Solution

- **Issue:** Copying data over a network takes time
- **Idea:**
  - Bring computation close to the data
  - Store files multiple times for reliability
- **Map-reduce addresses these problems**
  - Google's computational/data manipulation model
  - Elegant way to work with big data
  - **Storage Infrastructure – File system**
    - Google: GFS. Hadoop: HDFS
  - **Programming model**
    - Map-Reduce



# Storage Infrastructure

- **Problem:**

- If nodes fail, how to store data persistently?

- **Answer:**

- **Distributed File System:**

- Provides global file namespace
    - Google GFS; Hadoop HDFS;

- **Typical usage pattern**

- Huge files (100s of GB to TB)
  - Data is rarely updated in place
  - Reads and appends are common

# Distributed File System

## ■ Chunk servers

- File is split into contiguous chunks
- Typically each chunk is 16-64MB
- Each chunk replicated (usually 2x or 3x)
- Try to keep replicas in different racks

## ■ Master node

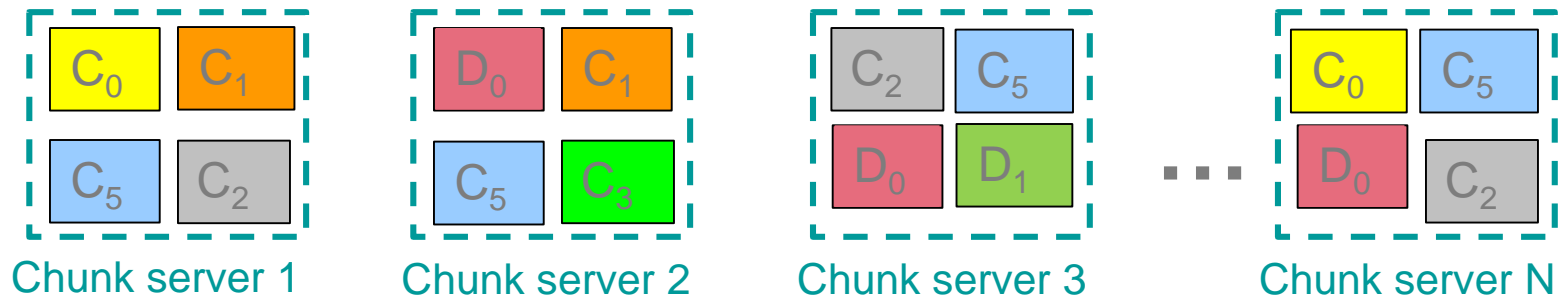
- a.k.a. Name Node in Hadoop's HDFS
- Stores metadata about where files are stored
- Might be replicated

## ■ Client library for file access

- Talks to master to find chunk servers
- Connects directly to chunk servers to access data

# Distributed File System

- **Reliable distributed file system**
- Data kept in “chunks” spread across machines
- Each chunk **replicated** on different machines
  - Seamless recovery from disk or machine failure



Bring computation directly to the data!

Chunk servers also serve as compute servers

# Programming Model: MapReduce

## Warm-up task:

- We have a huge text document
- Count the number of times each distinct word appears in the file
- **Sample application:**
  - Analyze web server logs to find popular URLs

# Task: Word Count

## Case 1:

- File too large for memory, but all `<word, count>` pairs fit in memory

## Case 2:

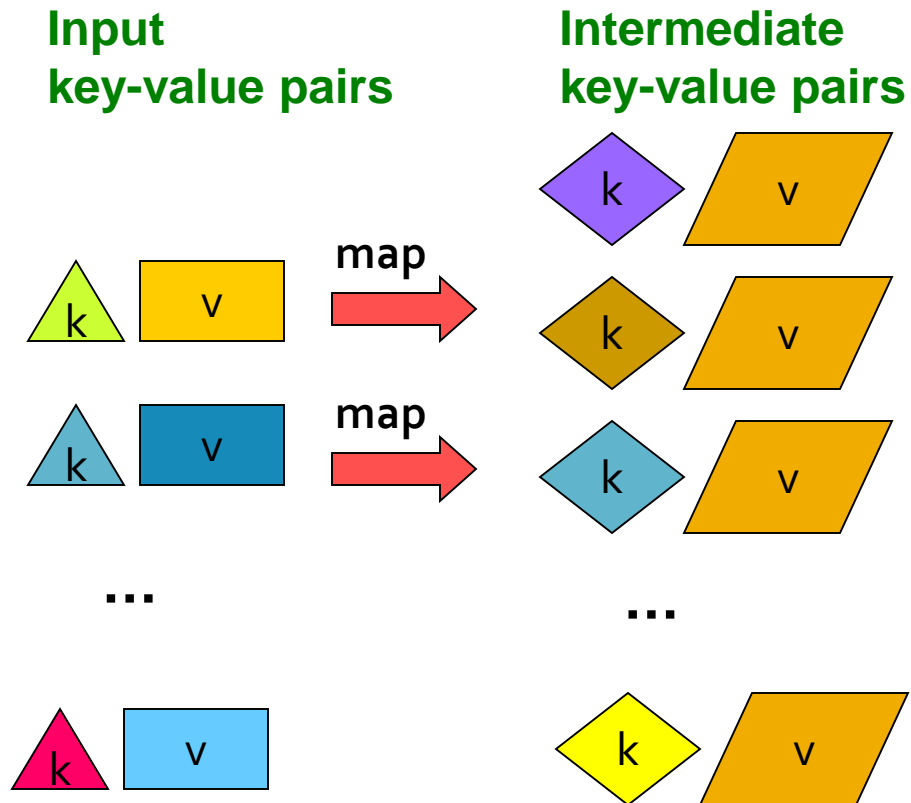
- Count occurrences of words:
  - `words (doc.txt) | sort | uniq -c`
    - where `words` takes a file and outputs the words in it, one per a line
- Case 2 captures the essence of **MapReduce**
  - Great thing is that it is naturally parallelizable

# MapReduce: Overview

- Sequentially read a lot of data
- **Map:**
  - Extract something you care about
- **Group by key:** Sort and Shuffle
- **Reduce:**
  - Aggregate, summarize, filter or transform
- Write the result

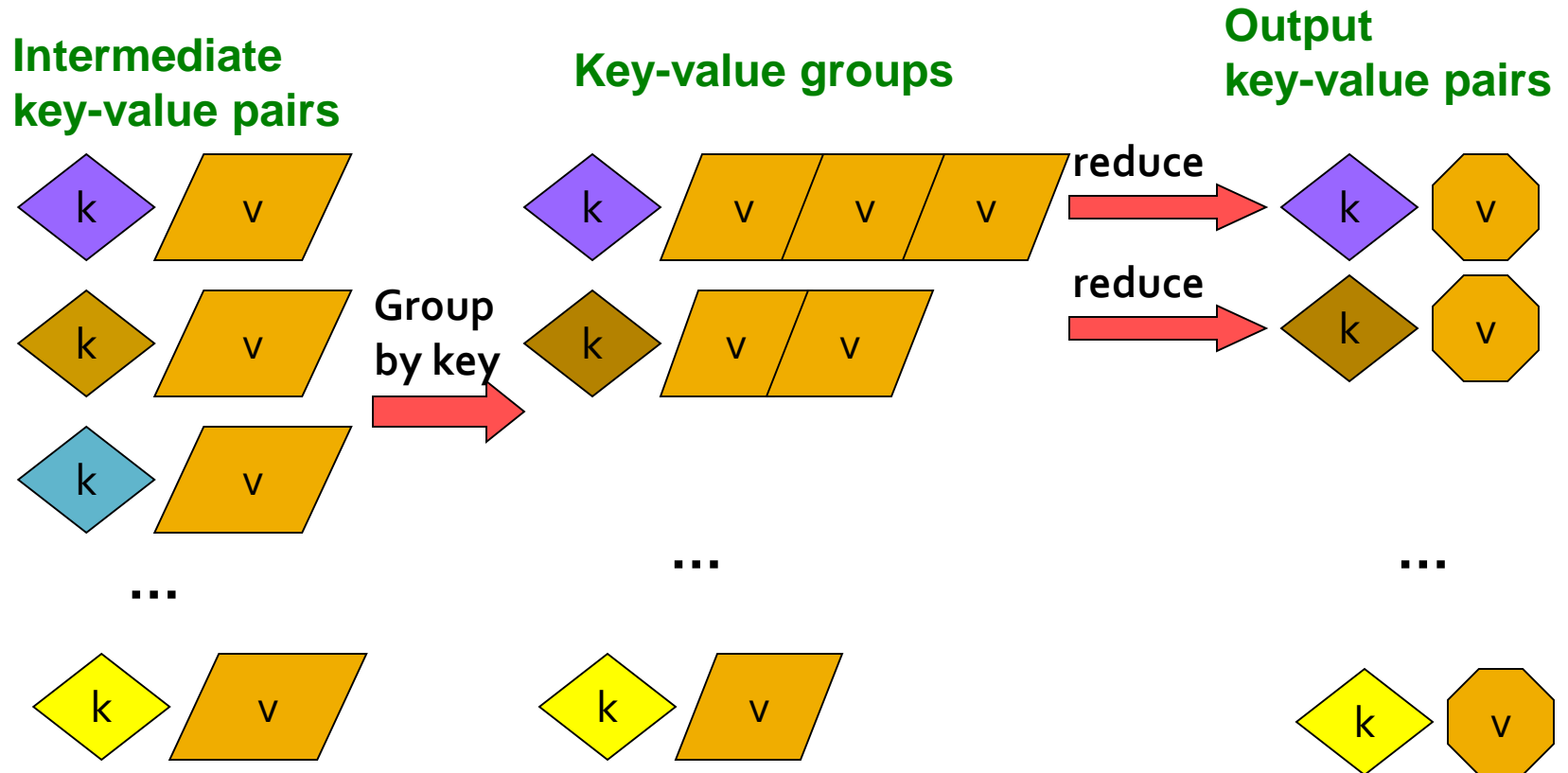
Outline stays the same, **Map** and **Reduce**  
change to fit the problem

# MapReduce: The Map Step





# MapReduce: The Reduce Step



# More Specifically

- **Input:** a set of key-value pairs
- Programmer specifies two methods:
  - **Map( $k, v$ )**  $\rightarrow \langle k', v' \rangle^*$ 
    - Takes a key-value pair and outputs a set of key-value pairs
      - E.g., key is the filename, value is a single line in the file
    - There is one Map call for every  $(k, v)$  pair
  - **Reduce( $k', \langle v' \rangle^*$ )**  $\rightarrow \langle k', v'' \rangle^*$ 
    - **All values  $v'$  with same key  $k'$  are reduced together and processed in  $v'$  order**
    - There is one Reduce function call per unique key  $k'$

# MapReduce: Word Counting

Provided by the  
programmer

## MAP:

Read input and  
produces a set of  
key-value pairs

(The, 1)

(crew, 1)

(of, 1)

(the, 1)

(space, 1)

(shuttle, 1)

(Endeavor, 1)

(recently, 1)

....

(key, value)

## Group by key:

Collect all pairs  
with same key

(crew, 1)

(crew, 1)

(space, 1)

(the, 1)

(the, 1)

(the, 1)

(shuttle, 1)

(recently, 1)

...

(key, value)

Provided by the  
programmer

## Reduce:

Collect all values  
belonging to the  
key and output

(crew, 2)

(space, 1)

(the, 3)

(shuttle, 1)

(recently, 1)

...

(key, value)

Only sequential reads

The crew of the space shuttle Endeavor recently returned to Earth as ambassadors, harbingers of a new era of space exploration. Scientists at NASA are saying that the recent assembly of the Dextre bot is the first step in a long-term space-based man/machine partnership. "The work we're doing now -- the robotics we're doing - is what we're going to need .....

Big document

# Word Count Using MapReduce

**map(key, value) :**

```
// key: document name; value: text of the document
  for each word w in value:
    emit(w, 1)
```

**reduce(key, values) :**

```
// key: a word; value: an iterator over counts
  result = 0
  for each count v in values:
    result += v
  emit(key, result)
```

# Map-Reduce: Environment

## Map-Reduce environment takes care of:

- Partitioning the input data
- Scheduling the program's execution across a set of machines
- Performing the **group by key** step
- Handling machine failures
- Managing required inter-machine communication

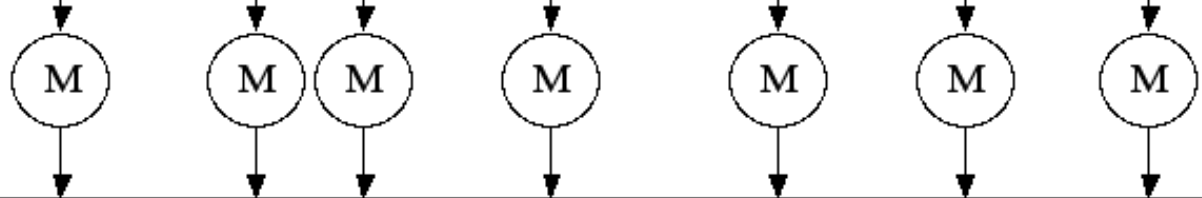
# Map-Reduce: A diagram

Input

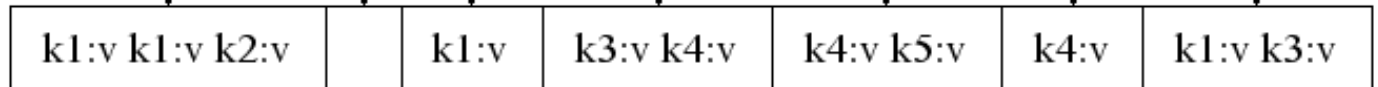


## MAP:

Read input and produces a set of key-value pairs

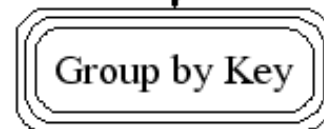


Intermediate

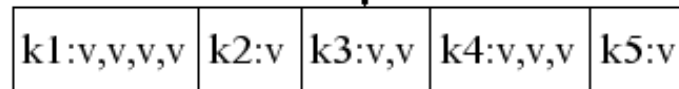


## Group by key:

Collect all pairs with same key  
(Hash merge, Shuffle, Sort, Partition)

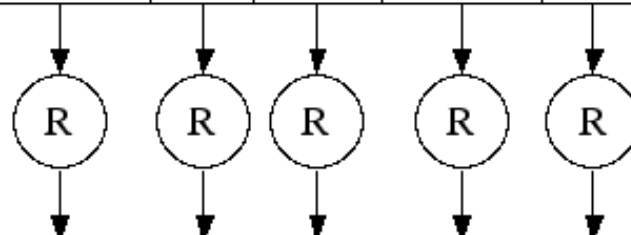


Grouped



## Reduce:

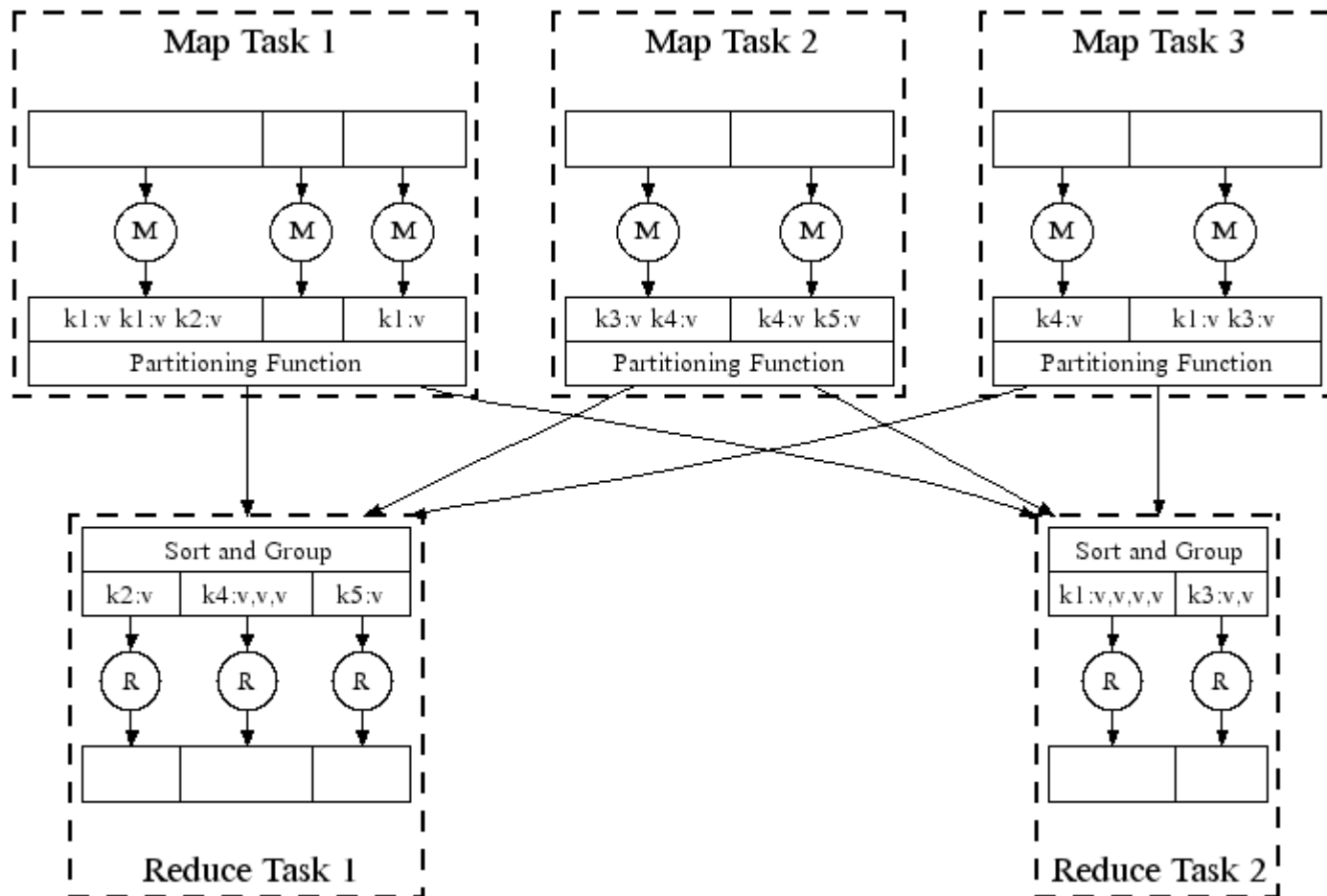
Collect all values belonging to the key and output



Output



# Map-Reduce: In Parallel

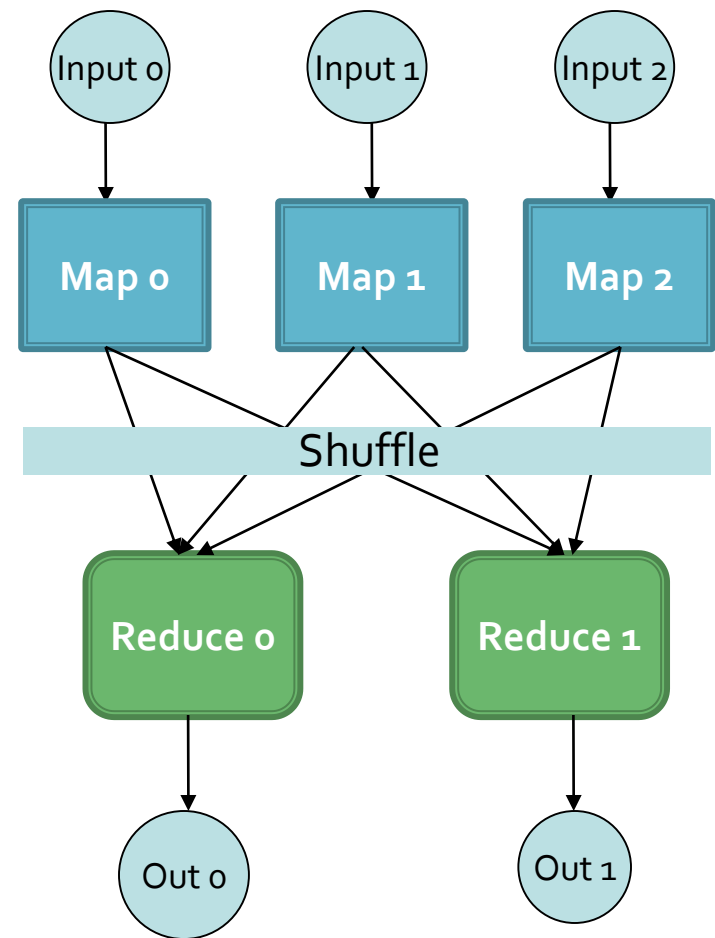


All phases are distributed with many tasks doing the work



# Map-Reduce

- **Programmer specifies:**
  - Map and Reduce and input files
- **Workflow:**
  - Read inputs as a set of key-value-pairs
  - **Map** transforms input kv-pairs into a new set of k'v'-pairs
  - Sorts & Shuffles the k'v'-pairs to output nodes
  - All k'v'-pairs with a given k' are sent to the same **reduce**
  - **Reduce** processes all k'v'-pairs grouped by key into new k''v''-pairs
  - Write the resulting pairs to files
- **All phases are distributed with many tasks doing the work**



# Data Flow

- **Input and final output are stored on a distributed file system (FS):**
  - Scheduler tries to schedule map tasks “close” to physical storage location of input data
- **Intermediate results are stored on local FS of Map and Reduce workers**
- **Output is often input to another MapReduce task**

# Coordination: Master

- **Master node takes care of coordination:**
  - **Task status:** (idle, in-progress, completed)
  - **Idle tasks** get scheduled as workers become available
  - When a map task completes, it sends the master the location and sizes of its  $R$  intermediate files, one for each reducer
  - Master pushes this info to reducers
- Master pings workers periodically to detect failures

# Dealing with Failures

## ■ Map worker failure

- Map tasks completed or in-progress at worker are reset to idle
- Reduce workers are notified when task is rescheduled on another worker

## ■ Reduce worker failure

- Only in-progress tasks are reset to idle
- Reduce task is restarted

## ■ Master failure

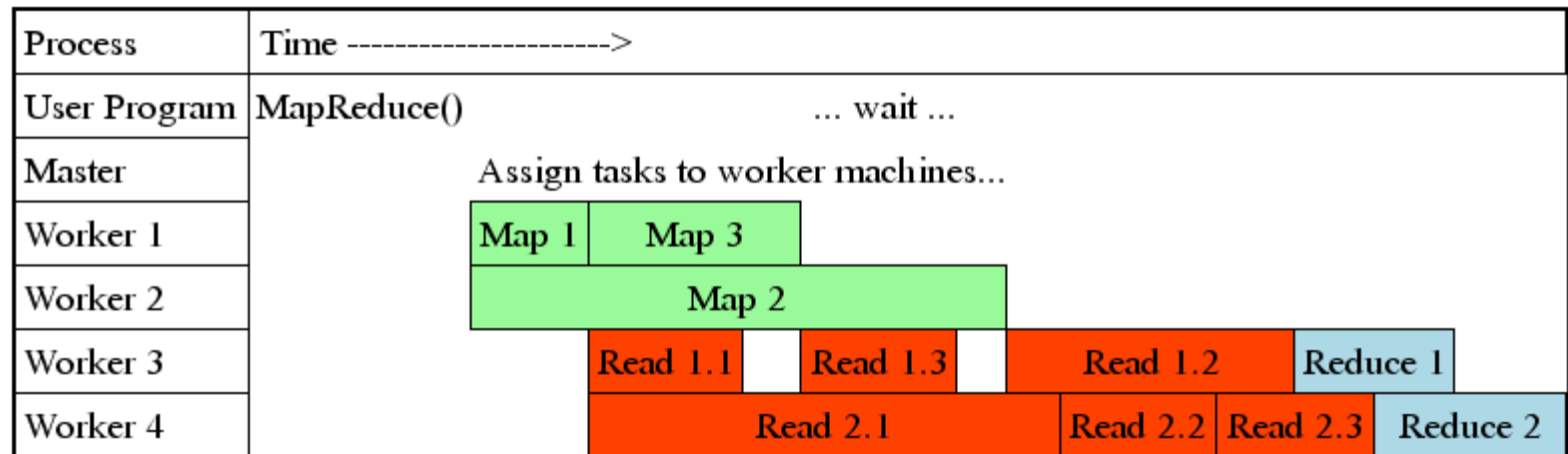
- MapReduce task is aborted and client is notified

# How many Map and Reduce jobs?

- $M$  map tasks,  $R$  reduce tasks
- **Rule of a thumb:**
  - Make  $M$  much larger than the number of nodes in the cluster
  - One DFS chunk per map is common
  - Improves dynamic load balancing and speeds up recovery from worker failures
- **Usually  $R$  is smaller than  $M$** 
  - Because output is spread across  $R$  files

# Task Granularity & Pipelining

- **Fine granularity tasks:** map tasks  $\gg$  machines
  - Minimizes time for fault recovery
  - Can do pipeline shuffling with map execution
  - Better dynamic load balancing



# Refinements: Backup Tasks

## ■ Problem

- Slow workers significantly lengthen the job completion time:
  - Other jobs on the machine
  - Bad disks
  - Weird things

## ■ Solution

- Near end of phase, spawn backup copies of tasks
  - Whichever one finishes first “wins”

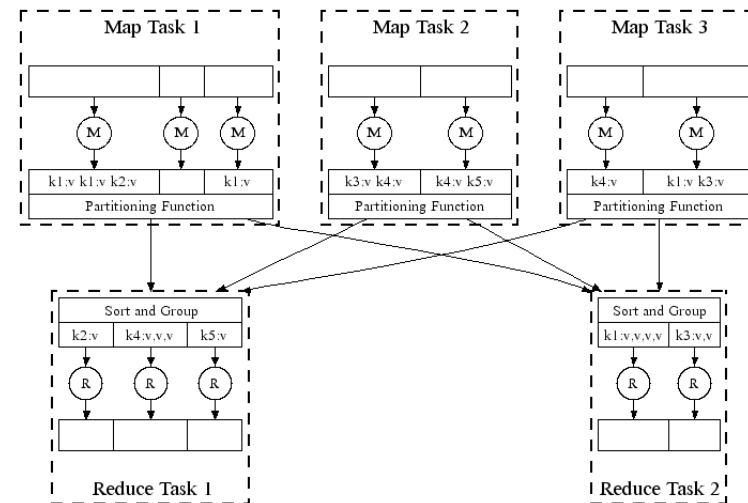
## ■ Effect

- Dramatically shortens job completion time



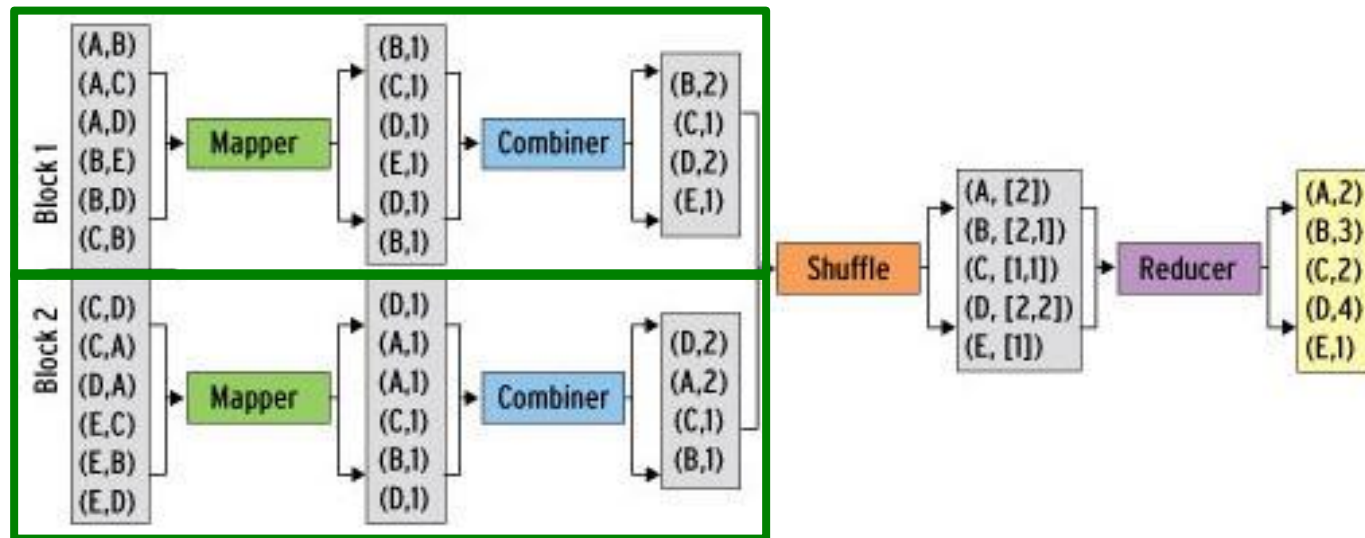
# Refinement: Combiners

- Often a Map task will produce many pairs of the form  $(k, v_1), (k, v_2), \dots$  for the same key  $k$ 
  - E.g., popular words in the word count example
- **Can save network time by pre-aggregating values in the mapper:**
  - $\text{combine}(k, \text{list}(v_1)) \rightarrow v_2$
  - Combiner is usually same as the reduce function
- Works only if reduce function is commutative and associative



# Refinement: Combiners

- **Back to our word counting example:**
  - Combiner combines the values of all keys of a single mapper (single machine):



- Much less data needs to be copied and shuffled!

# Refinement: Partition Function

- **Want to control how keys get partitioned**
  - Inputs to map tasks are created by contiguous splits of input file
  - Reduce needs to ensure that records with the same intermediate key end up at the same worker
- **System uses a default partition function:**
  - $\text{hash}(\text{key}) \bmod R$
- **Sometimes useful to override the hash function:**
  - E.g.,  $\text{hash}(\text{hostname}(\text{URL})) \bmod R$  ensures URLs from a host end up in the same output file

# Problems Suited for Map-Reduce

# Example: Host size

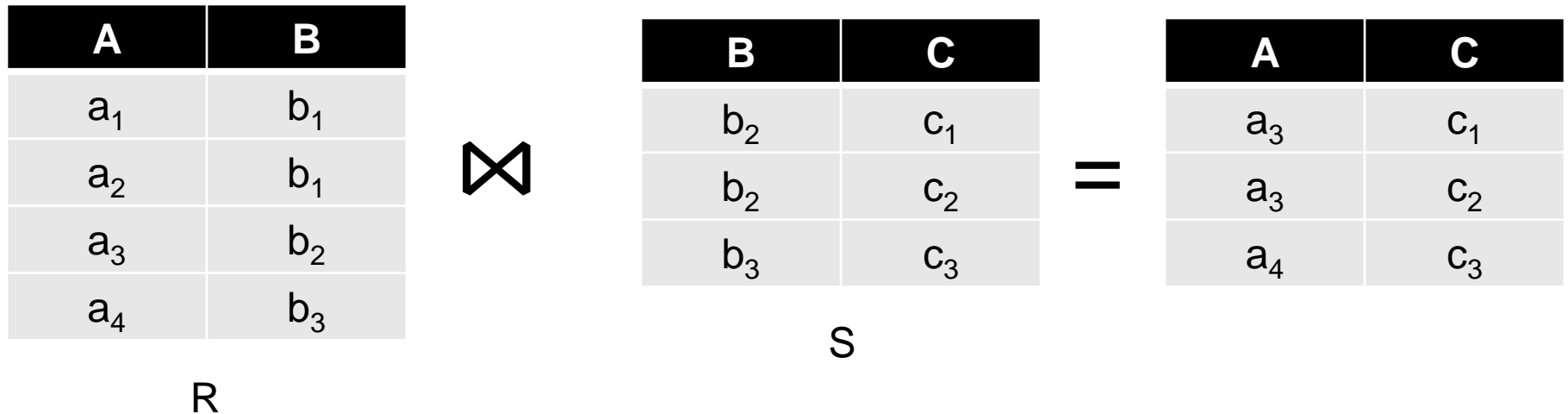
- **Suppose we have a large web corpus**
- **Look at the metadata file**
  - Lines of the form: (URL, size, date, ...)
- **For each host, find the total number of bytes**
  - That is, the sum of the page sizes for all URLs from that particular host
- **Other examples:**
  - Link analysis and graph processing
  - Machine Learning algorithms

# Example: Language Model

- **Statistical machine translation:**
  - Need to count number of times every 5-word sequence occurs in a large corpus of documents
- **Very easy with MapReduce:**
  - **Map:**
    - Extract (5-word sequence, count) from document
  - **Reduce:**
    - Combine the counts

# Example: Join By Map-Reduce

- Compute the natural join  $R(A,B) \bowtie S(B,C)$
- $R$  and  $S$  are each stored in files
- Tuples are pairs  $(a,b)$  or  $(b,c)$





# Map-Reduce Join

- Use a hash function  $h$  from B-values to  $1...k$
- **A Map process turns:**
  - Each input tuple  $R(a,b)$  into key-value pair  $(b,(a,R))$
  - Each input tuple  $S(b,c)$  into  $(b,(c,S))$
- **Map processes** send each key-value pair with key  $b$  to Reduce process  $h(b)$ 
  - Hadoop does this automatically; just tell it what  $k$  is.
- Each **Reduce process** matches all the pairs  $(b,(a,R))$  with all  $(b,(c,S))$  and outputs  $(a,b,c)$ .

# Cost Measures for Algorithms

- In MapReduce we quantify the cost of an algorithm using
  1. *Communication cost* = total I/O of all processes
  2. *Elapsed communication cost* = max of I/O along any path
  3. (*Elapsed*) *computation cost* analogous, but count only running time of processes

Note that here the big-O notation is not the most useful (adding more machines is always an option)

# Example: Cost Measures

- **For a map-reduce algorithm:**
  - **Communication cost** = input file size +  $2 \times$  (sum of the sizes of all files passed from Map processes to Reduce processes) + the sum of the output sizes of the Reduce processes.
  - **Elapsed communication cost** is the sum of the largest input + output for any map process, plus the same for any reduce process

# What Cost Measures Mean

- Either the I/O (communication) or processing (computation) cost dominates
  - Ignore one or the other
- Total cost tells what you pay in rent from your friendly neighborhood cloud
- Elapsed cost is wall-clock time using parallelism

# Cost of Map-Reduce Join

- **Total communication cost**  
 $= O(|R| + |S| + |R \bowtie S|)$
- **Elapsed communication cost**  $= O(s)$ 
  - We're going to pick  $k$  and the number of Map processes so that the I/O limit  $s$  is respected
  - We put a limit  $s$  on the amount of input or output that any one process can have.  **$s$  could be:**
    - What fits in main memory
    - What fits on local disk
- With proper indexes, computation cost is linear in the input + output size
  - So computation cost is like comm. cost

# Pointers and Further Reading

# Implementations

- Google
  - Not available outside Google
- **Hadoop**
  - An open-source implementation in Java
  - Uses HDFS for stable storage
  - Download: <http://lucene.apache.org/hadoop/>
- Aster Data
  - Cluster-optimized SQL Database that also implements MapReduce

# Cloud Computing

- Ability to rent computing by the hour
  - Additional services e.g., persistent storage
- Amazon's "Elastic Compute Cloud" (EC2)
- Aster Data and Hadoop can both be run on EC2



# Reading

- Jeffrey Dean and Sanjay Ghemawat:  
MapReduce: Simplified Data Processing on  
Large Clusters
  - <http://labs.google.com/papers/mapreduce.html>
- Sanjay Ghemawat, Howard Gobioff, and Shun-Tak Leung: The Google File System
  - <http://labs.google.com/papers/gfs.html>

# Resources

- Hadoop Wiki
  - Introduction
    - <http://wiki.apache.org/lucene-hadoop/>
  - Getting Started
    - <http://wiki.apache.org/lucene-hadoop/GettingStartedWithHadoop>
  - Map/Reduce Overview
    - <http://wiki.apache.org/lucene-hadoop/HadoopMapReduce>
    - <http://wiki.apache.org/lucene-hadoop/HadoopMapRedClasses>
  - Eclipse Environment
    - <http://wiki.apache.org/lucene-hadoop/EclipseEnvironment>
- Javadoc
  - <http://lucene.apache.org/hadoop/docs/api/>

# Resources

- Releases from Apache download mirrors
  - <http://www.apache.org/dyn/closer.cgi/lucene/hadoop/>
- Nightly builds of source
  - <http://people.apache.org/dist/lucene/hadoop/nightly/>
- Source code from subversion
  - [http://lucene.apache.org/hadoop/version\\_control.html](http://lucene.apache.org/hadoop/version_control.html)

# Further Reading

- Programming model inspired by functional language primitives
- Partitioning/shuffling similar to many large-scale sorting systems
  - NOW-Sort ['97]
- Re-execution for fault tolerance
  - BAD-FS ['04] and TACC ['97]
- Locality optimization has parallels with Active Disks/Diamond work
  - Active Disks ['01], Diamond ['04]
- Backup tasks similar to Eager Scheduling in Charlotte system
  - Charlotte ['96]
- Dynamic load balancing solves similar problem as River's distributed queues
  - River ['99]