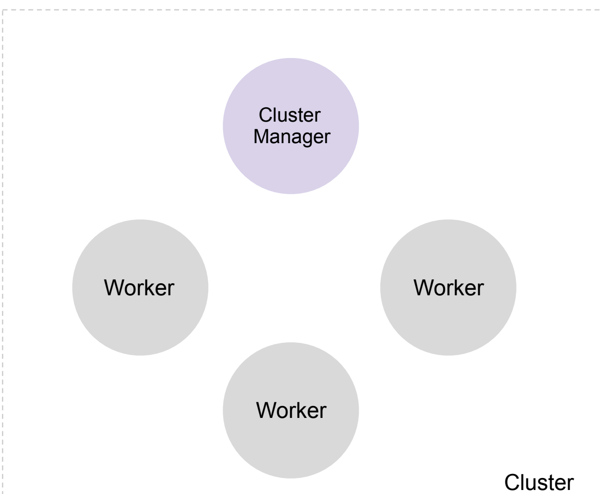
Batch Processing

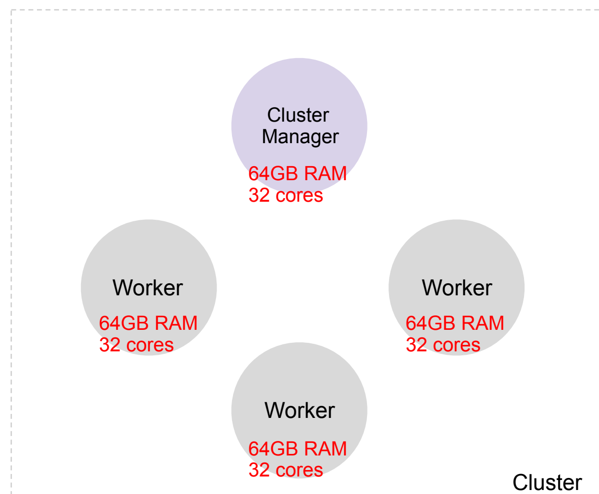
COS 518: *Distributed Systems*
Lecture 10

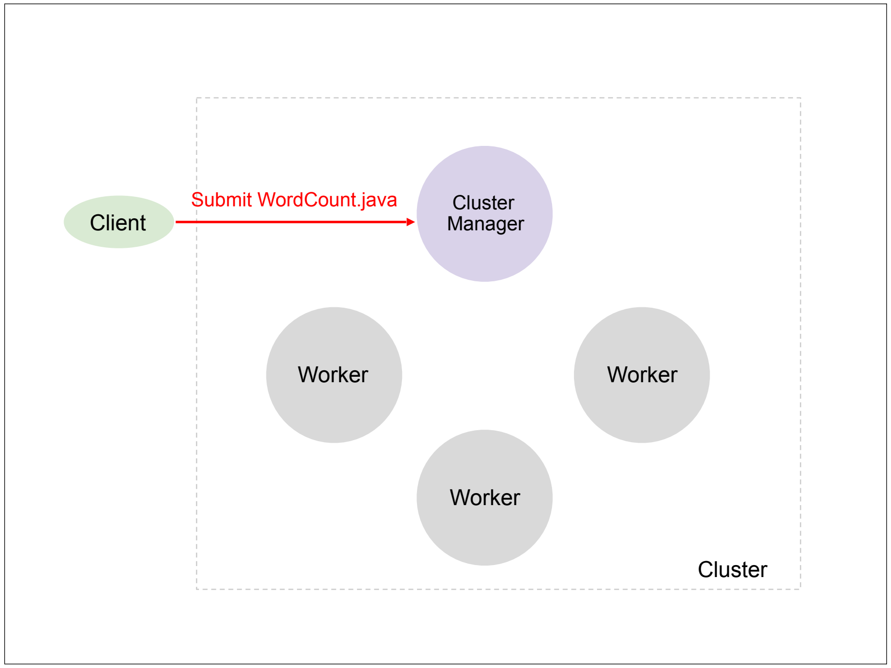
Andrew Or, Mike Freedman

Basic architecture

in “big data” systems






Client
Submit WordCount.java
Cluster Manager
Worker
Worker
Worker
Cluster

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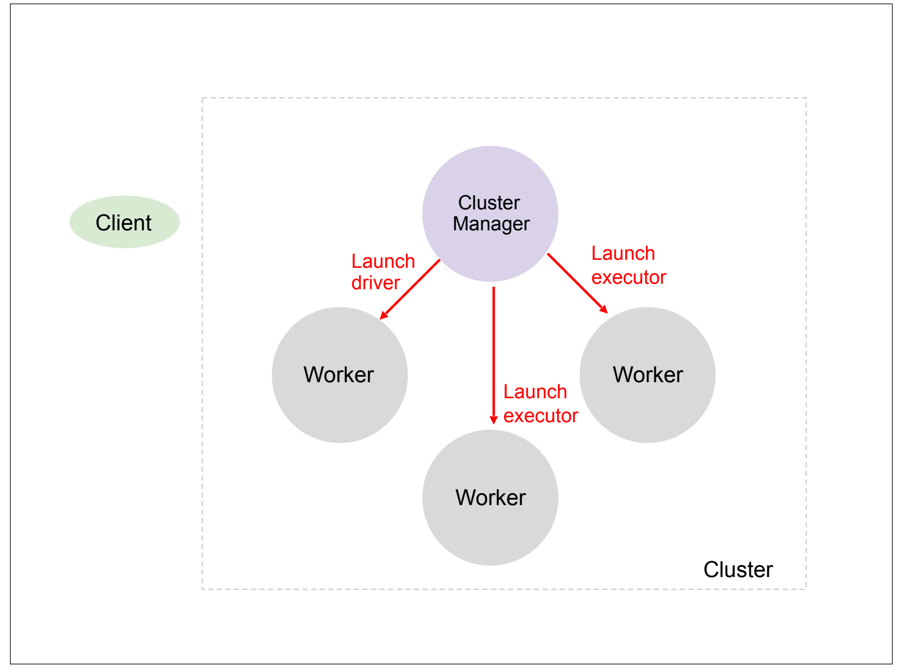
Client
Cluster Manager
Launch driver
Launch executor
Launch executor
Worker
Worker
Worker
Cluster

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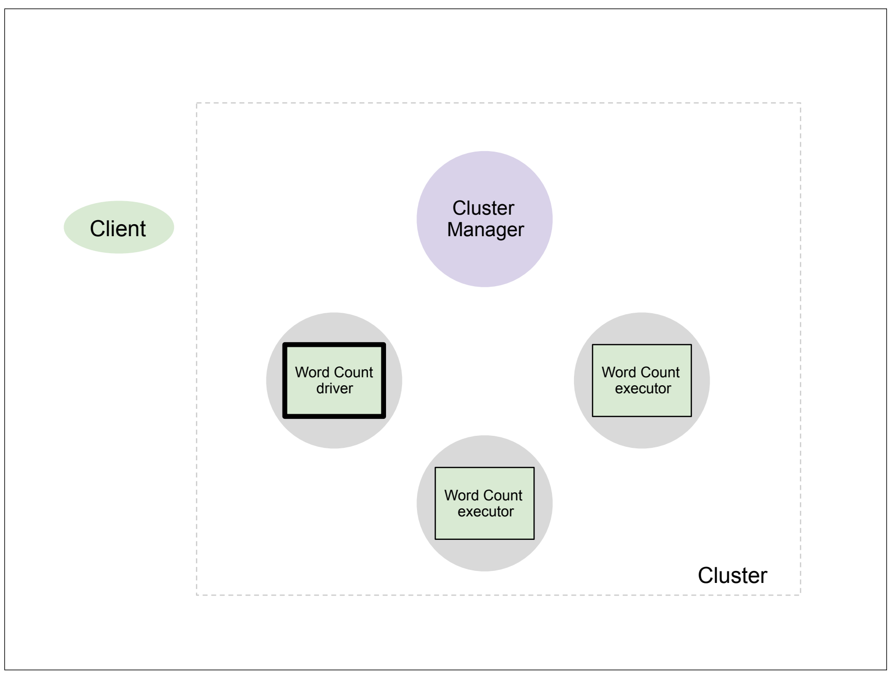
Client
Cluster Manager
Word Count driver
Word Count executor
Word Count executor
Cluster

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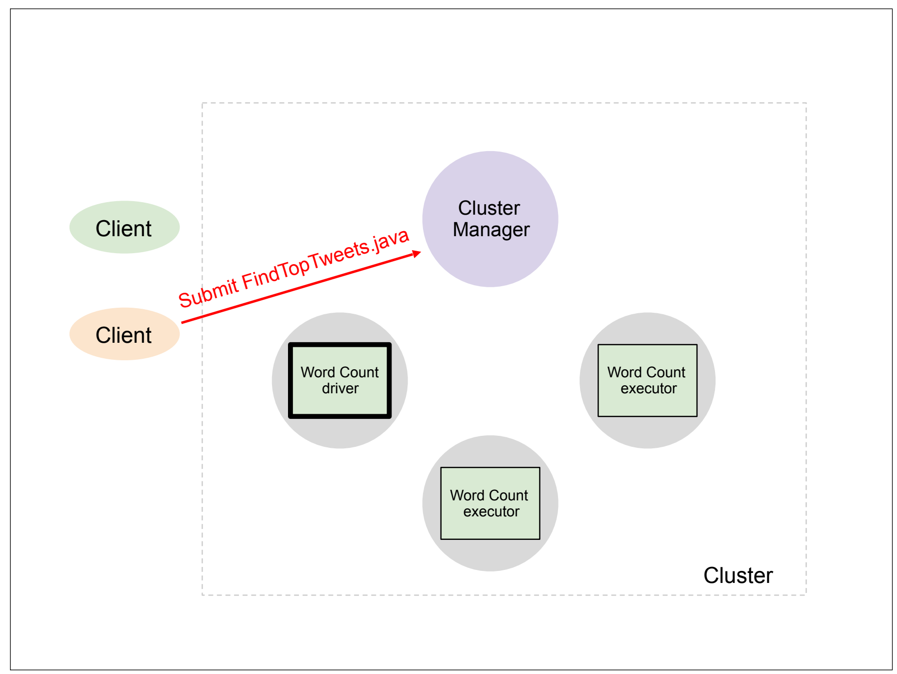
Client
Client
Submit FindTopTweets.java
Cluster Manager
Word Count driver
Word Count executor
Word Count executor
Cluster

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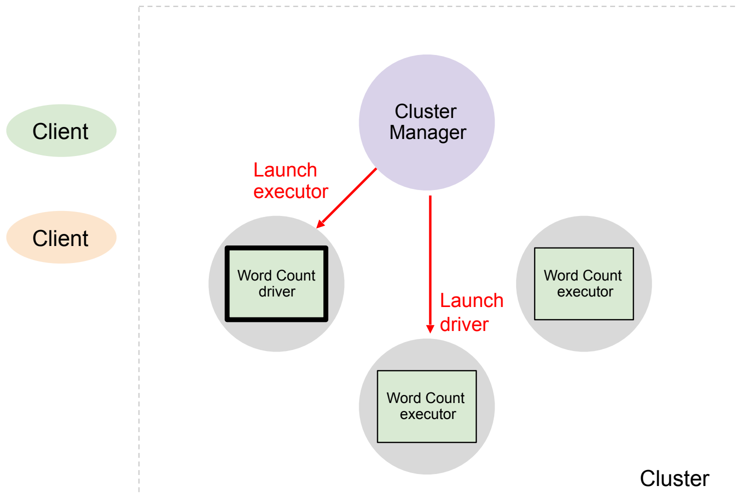

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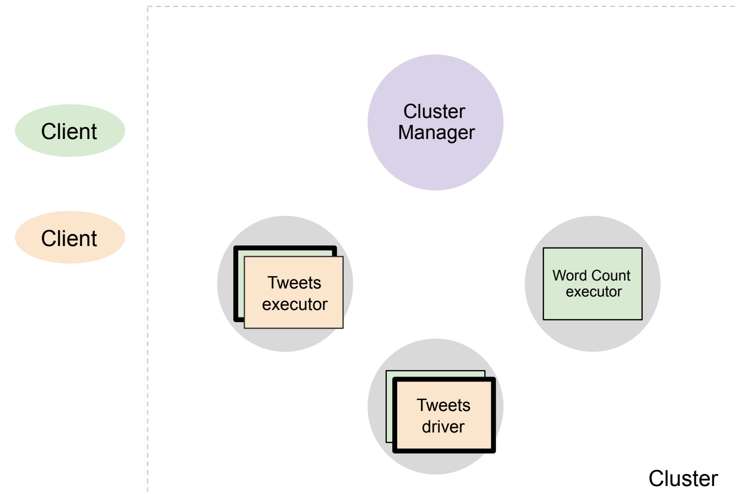

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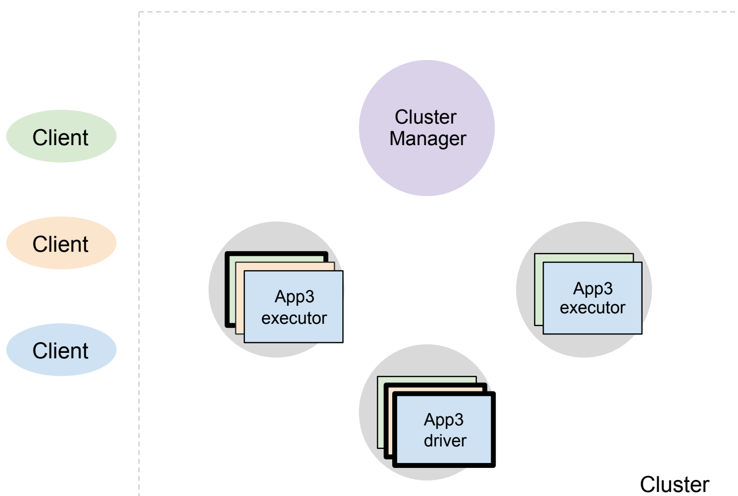

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Basic architecture

Clients submit applications to the cluster manager

Cluster manager assigns cluster resources to applications

Each Worker launches containers for each application

Driver containers run main method of user program

Executor containers run actual computation

Examples of cluster manager: YARN, Mesos

Examples of computing frameworks: Hadoop MapReduce, Spark

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Two levels of scheduling

Cluster-level: Cluster manager assigns resources to applications

Application-level: Driver assigns *tasks* to run on executors

A task is a unit of execution that operates on one *partition*

Some advantages:

Applications need not be concerned with resource fairness

Cluster manager need not be concerned with individual tasks

Easy to implement priorities and preemption

Case Study: MapReduce

(Data-parallel programming at scale)

Application: Word count

Hello my love. I love you, my dear. Goodbye.

↓

hello: 1, my: 2, love: 2, i: 1, dear: 1, goodbye: 1

Application: Word count

Locally: tokenize and put words in a hash map

How do you parallelize this?

Split document by half

Build two hash maps, one for each half

Merge the two hash maps (by key)

How do you do this in a distributed environment?

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When in the Course of human events, it becomes necessary for one people to dissolve the political bands which have connected them with another, and to assume, among the Powers of the earth, the separate and equal station to which the Laws of Nature and of Nature's God entitle them, a decent respect to the opinions of mankind requires that they should declare the causes which impel them to the separation.

Input document

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When in the Course of human events, it becomes necessary for one people to

dissolve the political bands which have connected them with another, and to assume,

among the Powers of the earth, the separate and equal station to which the Laws of

Nature and of Nature's God entitle them, a decent respect to the opinions of mankind

requires that they should declare the causes which impel them to the separation.

Partition

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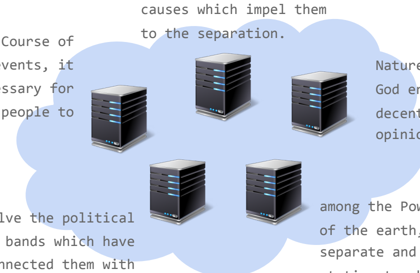

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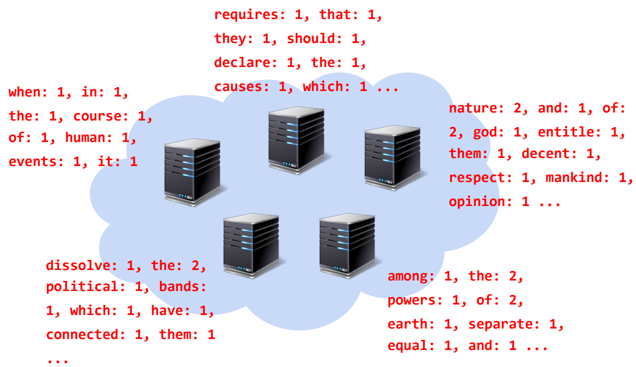
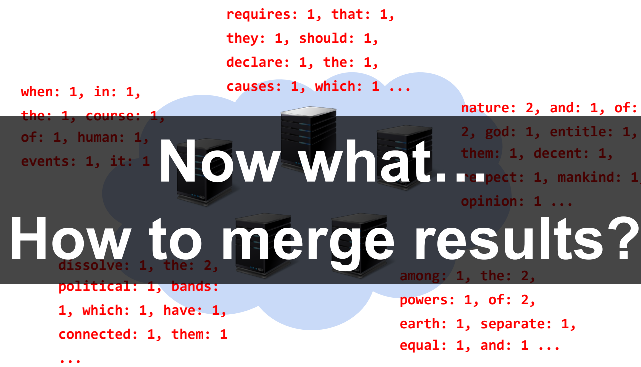


Compute word counts locally



Now what…

How to merge results?

Compute word counts locally

Merging results computed locally

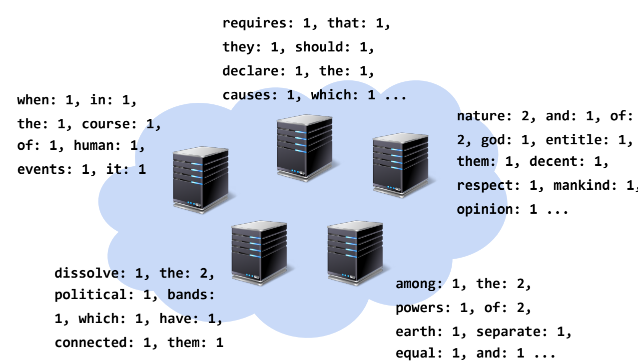
Several options

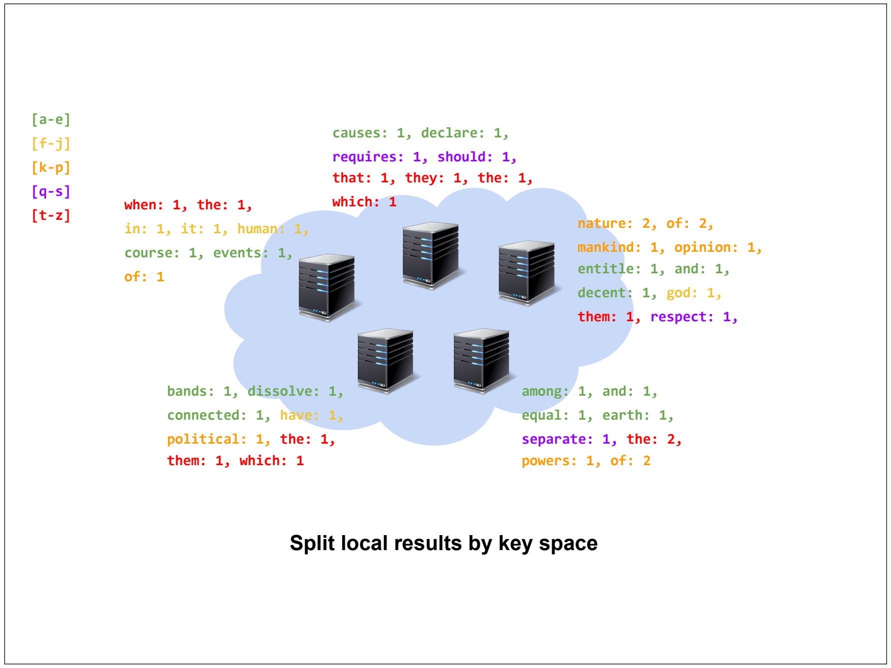
Don't merge — requires additional computation for correct results

Send everything to one node — what if data is too big? Too slow…

Partition key space among nodes in cluster (e.g. [a-e], [f-j], [k-p] ...)

1. Assign a key space to each node
2. Partition local results by the key spaces
3. Fetch and merge results that correspond to the node's key space




[a-e]
[f-j]
[k-p]
[q-s]
[t-z]
causes: 1, declare: 1,
requires: 1, should: 1,
that: 1, they: 1, the: 1,
which: 1
when: 1, the: 1,
in: 1, it: 1, human: 1,
course: 1, events: 1,
of: 1
nature: 2, of: 2,
mankind: 1, opinion: 1,
entitle: 1, and: 1,
decent: 1, god: 1,
them: 1, respect: 1,
bands: 1, dissolve: 1,
connected: 1, have: 1,
political: 1, the: 1,
them: 1, which: 1
among: 1, and: 1,
equal: 1, earth: 1,
separate: 1, the: 2,
powers: 1, of: 2
Split local results by key space

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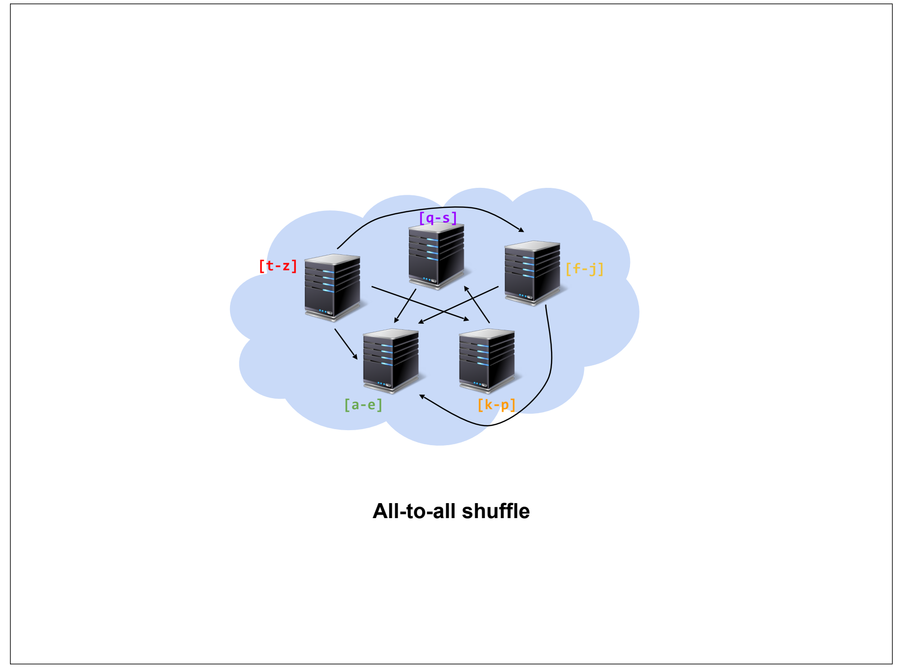
[q-s]
[t-z]
[f-j]
[a-e]
[k-p]
All-to-all shuffle

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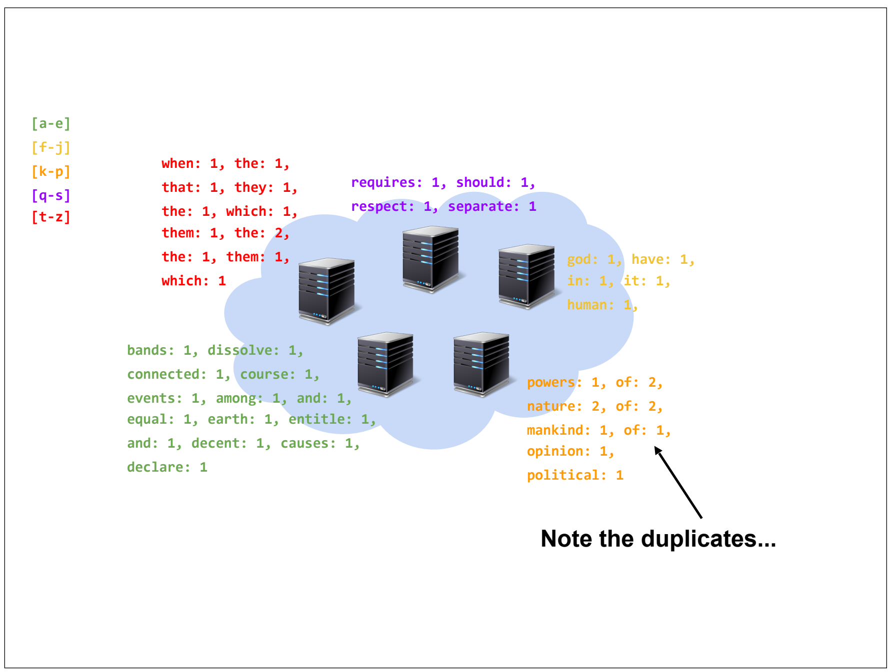
[a-e]
[f-j]
[k-p]
[q-s]
[t-z]
when: 1, the: 1,
that: 1, they: 1,
the: 1, which: 1,
them: 1, the: 2,
the: 1, them: 1,
which: 1
requires: 1, should: 1,
respect: 1, separate: 1
god: 1, have: 1,
in: 1, it: 1,
human: 1,
bands: 1, dissolve: 1,
connected: 1, course: 1,
events: 1, among: 1, and: 1,
equal: 1, earth: 1, entitle: 1,
and: 1, decent: 1, causes: 1,
declare: 1
powers: 1, of: 2,
nature: 2, of: 2,
mankind: 1, of: 1,
opinion: 1,
political: 1
Note the duplicates...

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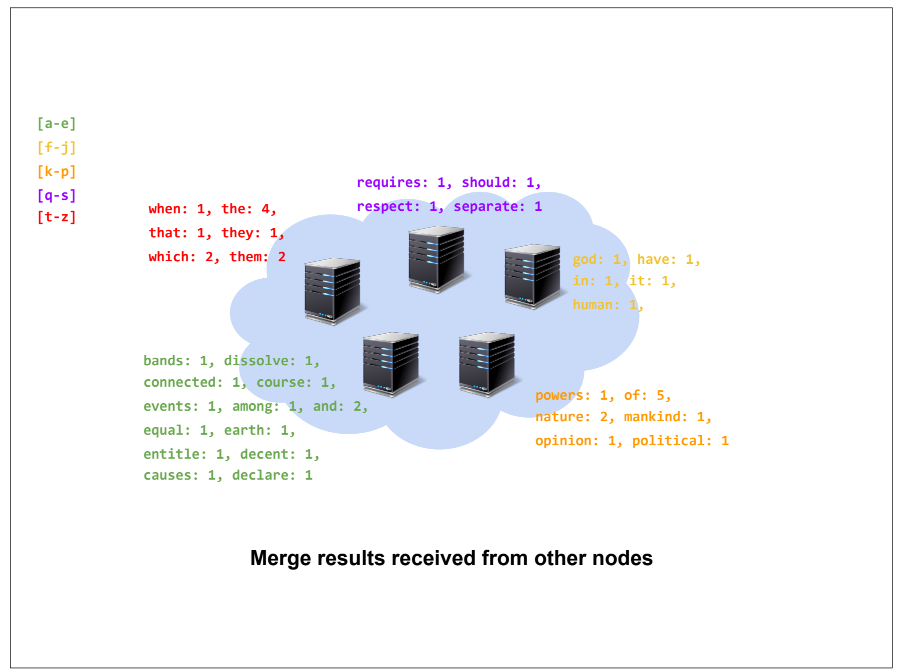
[a-e]
[f-j]
[k-p]
[q-s]
[t-z]
requires: 1, should: 1,
respect: 1, separate: 1
when: 1, the: 4,
that: 1, they: 1,
which: 2, them: 2
god: 1, have: 1,
in: 1, it: 1,
human: 1,
bands: 1, dissolve: 1,
connected: 1, course: 1,
events: 1, among: 1, and: 2,
equal: 1, earth: 1,
entitle: 1, decent: 1,
causes: 1, declare: 1
powers: 1, of: 5,
nature: 2, mankind: 1,
opinion: 1, political: 1
Merge results received from other nodes

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MapReduce

Partition dataset into many chunks

Map stage: Each node processes one or more chunks locally

Reduce stage: Each node fetches and merges partial results from all other nodes

MapReduce Interface

`map(key, value) -> list(<k', v'>)`

Apply function to (key, value) pair

Outputs set of intermediate pairs

`reduce(key, list<value>) -> <k', v'>`

Applies aggregation function to values

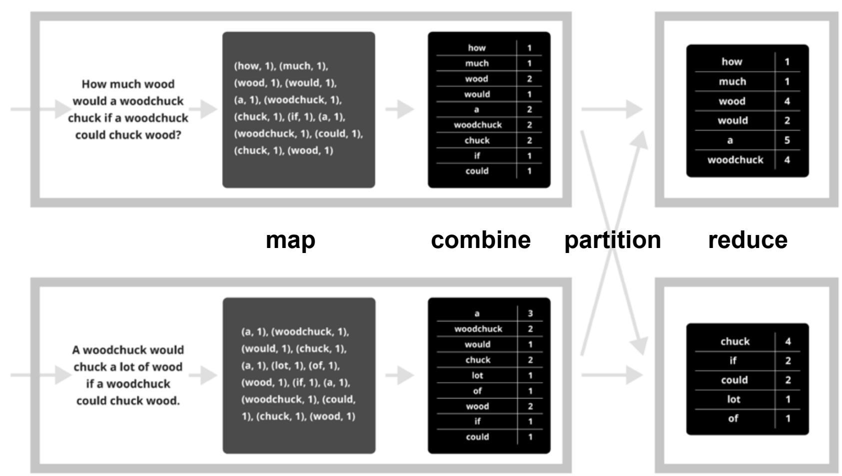
Outputs result

MapReduce: Word count

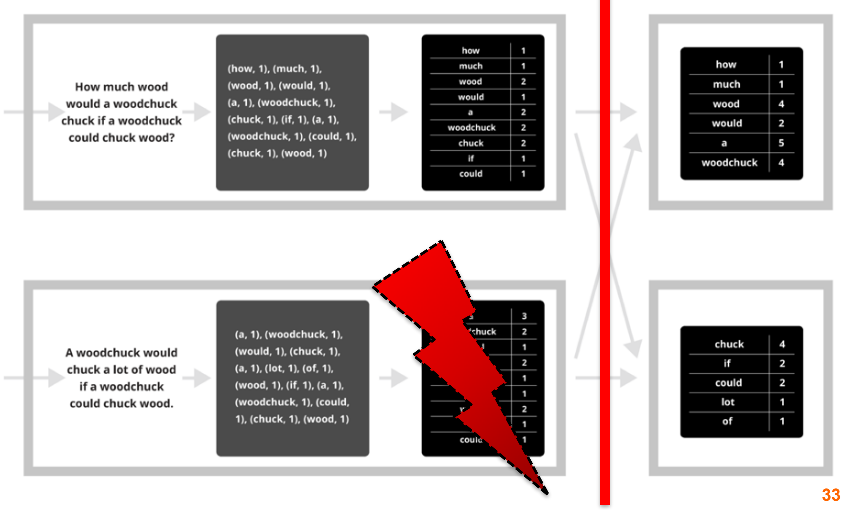
```
map(key, value):
   // key = document name
   // value = document contents
   for each word w in value:
     emit (w, 1)

reduce(key, values):
   // key = the word
   // values = number of occurrences of that word
   count = sum(values)
   emit (key, count)
```


MapReduce: Word count



Synchronization Barrier



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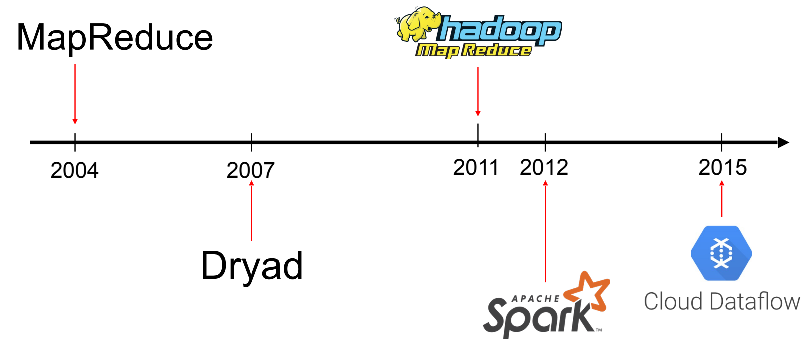

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Brainstorm: Top K

Top K is the problem of finding the largest K values from a set of numbers

How would you express this as a distributed application?

In particular, what would the map and reduce phases look like?

Hint: use a heap…

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Brainstorm: Top K

Assuming that a set of K integers fit in memory…

Key idea...

Map phase: everyone maintains a heap of K elements

Reduce phase: merge the heaps until you're left with one

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Brainstorm: Top K

Problem: What are the keys and values here?

No notion of key here, just assign the same key to all the values (e.g. key = 1)

Map task 1: [10, 5, 3, 700, 18, 4] → (1, heap(700, 18, 10))

Map task 2: [16, 4, 523, 100, 88] → (1, heap(523, 100, 88))

Map task 3: [3, 3, 3, 3, 300, 3] → (1, heap(300, 3, 3))

Map task 4: [8, 15, 20015, 89] → (1, heap(20015, 89, 15))

Then all the heaps will go to a single reducer responsible for the key 1

This works, but clearly not scalable…

Brainstorm: Top K

Idea: Use X different keys to balance load (e.g. X = 2 here)

Map task 1: [10, 5, 3, 700, 18, 4] → (1, heap(700, 18, 10))

Map task 2: [16, 4, 523, 100, 88] → (1, heap(523, 100, 88))

Map task 3: [3, 3, 3, 3, 300, 3] → (2, heap(300, 3, 3))

Map task 4: [8, 15, 20015, 89] → (2, heap(20015, 89, 15))

Then all the heaps will (hopefully) go to X different reducers

Rinse and repeat (*what's the runtime complexity?*)

Case Study: Spark

(Data-parallel programming at scale)

What is Spark?

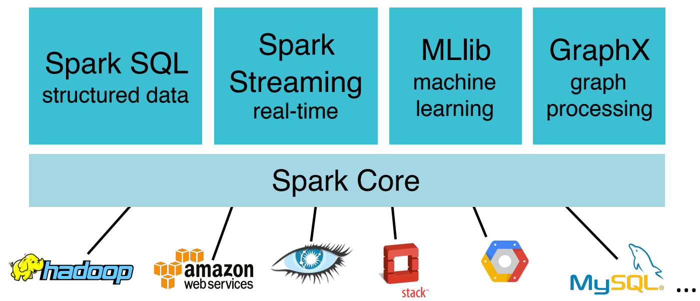
General distributed data execution engine

Key optimizations

- General computation graphs (pipelining, lazy execution)
- In-memory data sharing (caching)
- Fine-grained fault tolerance

#1 most active big data project

What is Spark?

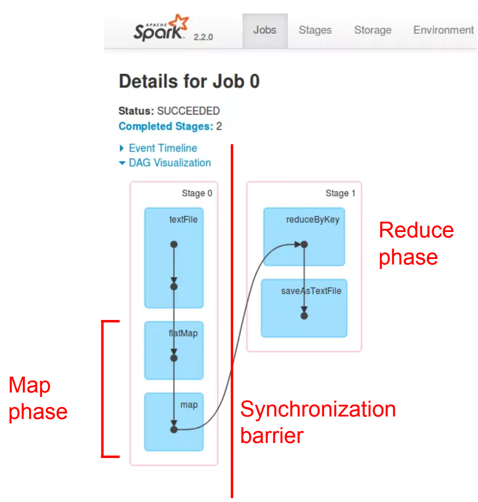


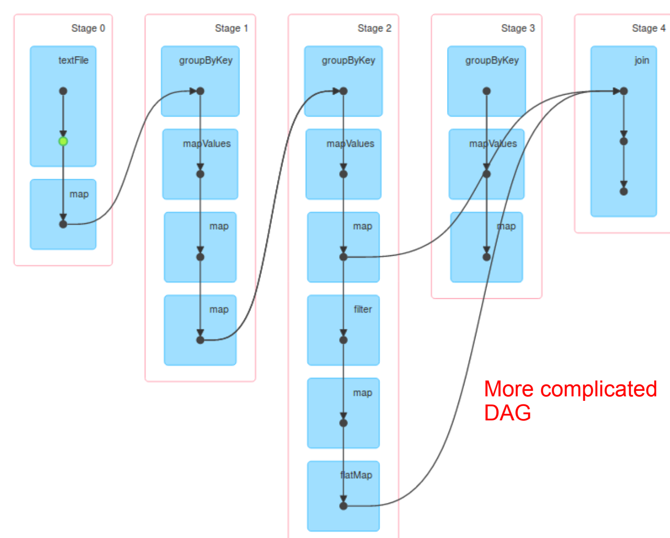
Spark computational model

Most computation can be expressed in terms of two phases

- Map phase defines how each machine processes its individual partition
- Reduce phase defines how to merge map outputs from previous phase

Spark expresses computation as a DAG of maps and reduces





Spark: Word count

Transformations express how to process a dataset

Actions express how to turn a transformed dataset into results

```
sc.textFile("declaration-of-independence.txt")
     .flatMap { line => line.split(" ") }
     .map { word => (word, 1) }
     .reduceByKey { case (counts1, counts2) => counts1 + counts2 }
     .collect()
```


Pipelining + Lazy execution

Transformations can be pipelined until we hit

A synchronization barrier (e.g. reduce), or

An action

Example:

```
data.map { ... }.filter { ... }.flatMap { ... }.groupByKey().count()
```

These three operations can all be run in the same task

This allows lazy execution; we don't need to eagerly execute map

In-memory caching

Store intermediate results in memory to bypass disk access

Important for iterative workloads (e.g. machine learning!)

Example:

```
val cached = data.map { ... }.filter { ... }.cache()
(1 to 100).foreach { i =>
    cached.reduceByKey { ... }.saveAsTextFile(...)
}
```


Reusing map outputs

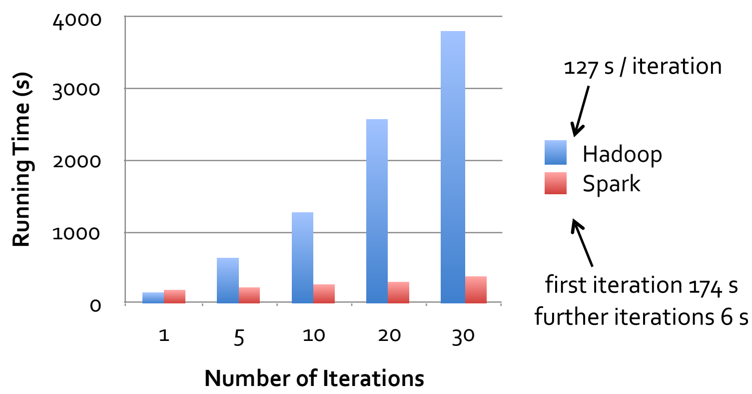
Reusing map outputs allows Spark to avoid redoing map stages

Along with caching, this makes iterative workloads much faster

Example:

```
val transformed = data.map { ... }.reduceByKey { ... }
transformed.collect()
transformed.collect() // does not run map phase again
```

Logistic Regression Performance



[Borrowed from Matei Zaharia's talk, "Spark: Fast, Interactive, Language-Integrated Cluster Computing"]

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Monday

Stream processing

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Application: Word Count

SELECT count(word) FROM data

GROUP BY word

cat data.txt

| tr -s '[[:punct:][:space:]]' '\n'

| sort | uniq -c

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Using partial aggregation

1. Compute word counts from individual files
2. Then merge intermediate output
3. Compute word count on merged outputs

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Using partial aggregation

1. In parallel, send to worker:
   - Compute word counts from individual files
   - Collect result, wait until all finished
2. Then merge intermediate output
3. Compute word count on merged intermediates

MapReduce: Programming Interface

```
map(key, value) -> list(<k', v'>)
```

- Apply function to (key, value) pair and produces set of intermediate pairs

```
reduce(key, list<value>) -> <k', v'>
```

- Applies aggregation function to values
- Outputs result

MapReduce: Programming Interface

```
map(key, value):
  for each word w in value:
    EmitIntermediate(w, "1");

reduce(key, list(values):
  int result = 0;
  for each v in values:
    result += ParseInt(v);
  Emit(AsString(result));
```


MapReduce: Optimizations

```
combine(list<key, value>) -> list<k,v>
```

- Perform partial aggregation on mapper node:

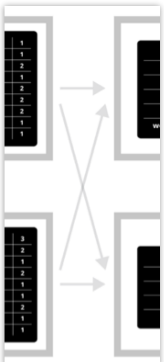
  <the, 1>, <the, 1>, <the, 1> → <the, 3>

- reduce() should be commutative and associative

```
partition(key, int) -> int
```

- Need to aggregate intermediate vals with same key
- Given n partitions, map key to partition $0 \le i < n$
- Typically via hash(key) mod n

Fault Tolerance in MapReduce

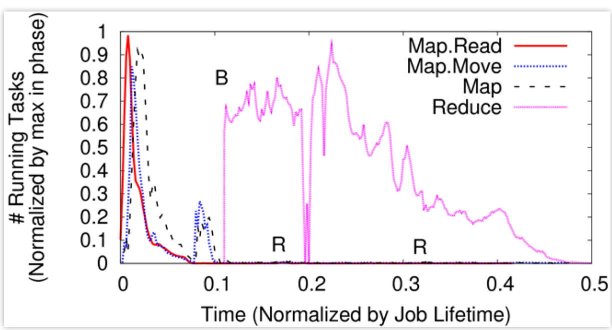


- Map worker writes intermediate output to local disk, separated by partitioning. Once completed, tells master node.
- Reduce worker told of location of map task outputs, pulls their partition's data from each mapper, execute function across data
- Note:
  - "All-to-all" shuffle b/w mappers and reducers
  - Written to disk ("materialized") b/w *each* stage

Fault Tolerance in MapReduce

- Master node monitors state of system
  - If master failures, job aborts and client notified
- Map worker failure
  - Both in-progress/completed tasks marked as idle
  - Reduce workers notified when map task is re-executed on another map worker
- Reducer worker failure
  - In-progress tasks are reset to idle (and re-executed)
  - Completed tasks had been written to global file system

Straggler Mitigation in MapReduce



- Tail latency means some workers finish late
- For slow map tasks, execute in parallel on second map worker as "backup", race to complete task