



Data-Intensive Distributed Computing

CS 451/651 431/631 (Winter 2018)

Part I: From MapReduce to Spark (1/2)
January 23, 2018

Jimmy Lin
David R. Cheriton School of Computer Science
University of Waterloo

These slides are available at <http://lintool.github.io/bigdata-2018w/>



This work is licensed under a Creative Commons Attribution-Noncommercial-Share Alike 3.0 United States
See <http://creativecommons.org/licenses/by-nc-sa/3.0/us/> for details



An Apt Quote

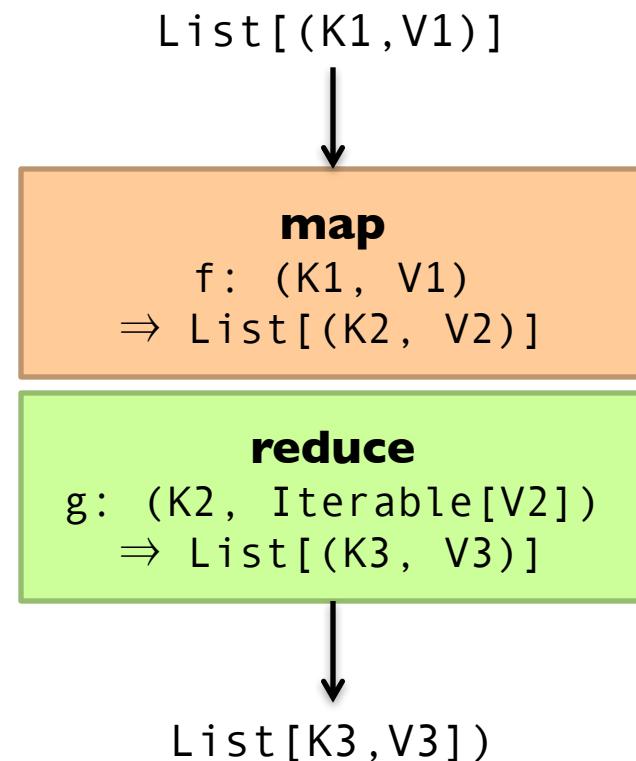
All problems in computer science can be solved
by another level of indirection... Except for the
problem of too many layers of indirection.

- David Wheeler

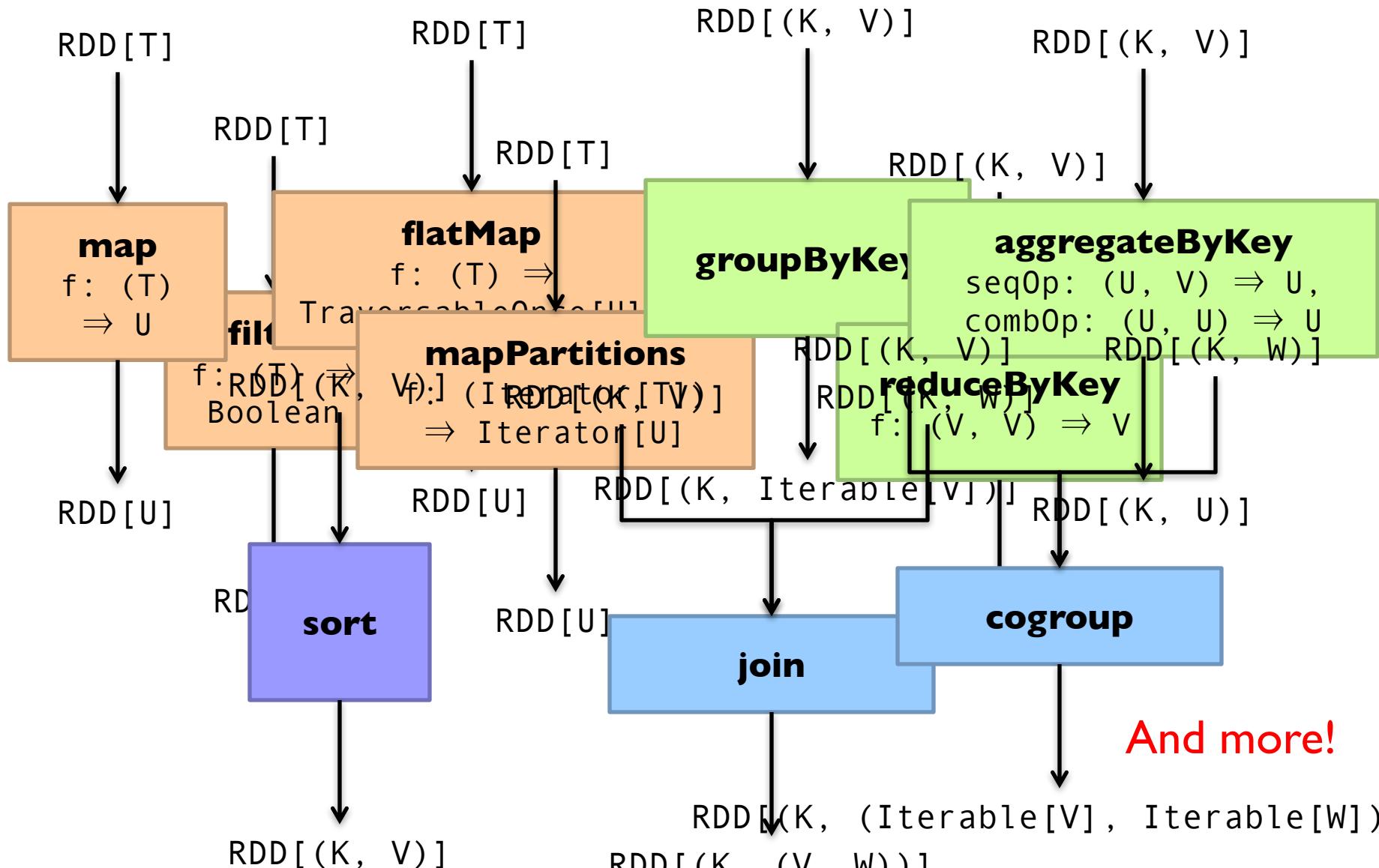
An aerial photograph of a large data center complex during sunset. The sky is a warm orange and yellow. In the foreground, there are several large white industrial buildings, some with flat roofs and others with green roofs. There are also numerous white shipping containers stacked in a row. A network of roads and parking lots connects the buildings. In the background, there are more industrial structures, a highway with traffic, and a vast, green, agricultural landscape stretching to the horizon.

The datacenter *is* the computer!
What's the instruction set?
What are the abstractions?

MapReduce



Spark

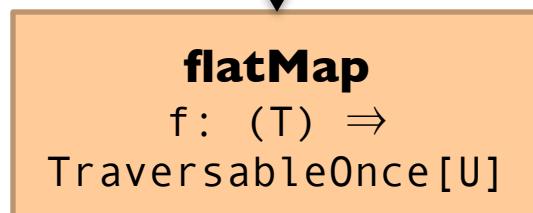


Spark Word Count

```
val textFile = sc.textFile(args.input())
```

```
textFile  
  .flatMap(line => tokenize(line))  
  .map(word => (word, 1))  
  .reduceByKey((x, y) => x + y)  
  .saveAsTextFile(args.output())
```

RDD[T] ??



RDD[U]

What's an RDD?

Resilient Distributed Dataset (RDD)

= immutable = partitioned

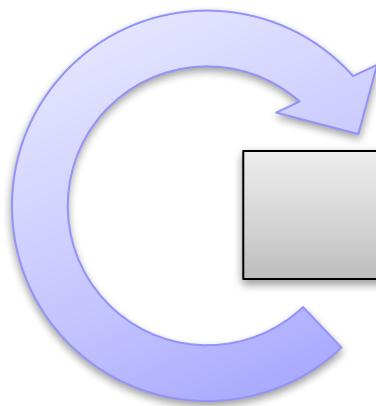
Wait, so how do you actually do anything?

Developers define *transformations* on RDDs

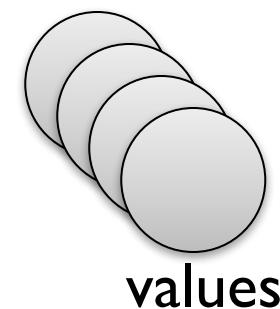
Framework keeps track of lineage

RDD Lifecycle

Transformation



Action



values

Transformations are lazy:
Framework keeps track of lineage

Actions trigger actual execution

Spark Word Count

RDDs

```
→ val textFile = sc.textFile(args.input())
```

```
→ val a = textFile.flatMap(line => line.split(" ")) ←
```

```
→ val b = a.map(word => (word, 1)) ←
```

```
→ val c = b.reduceByKey((x, y) => x + y) ←
```

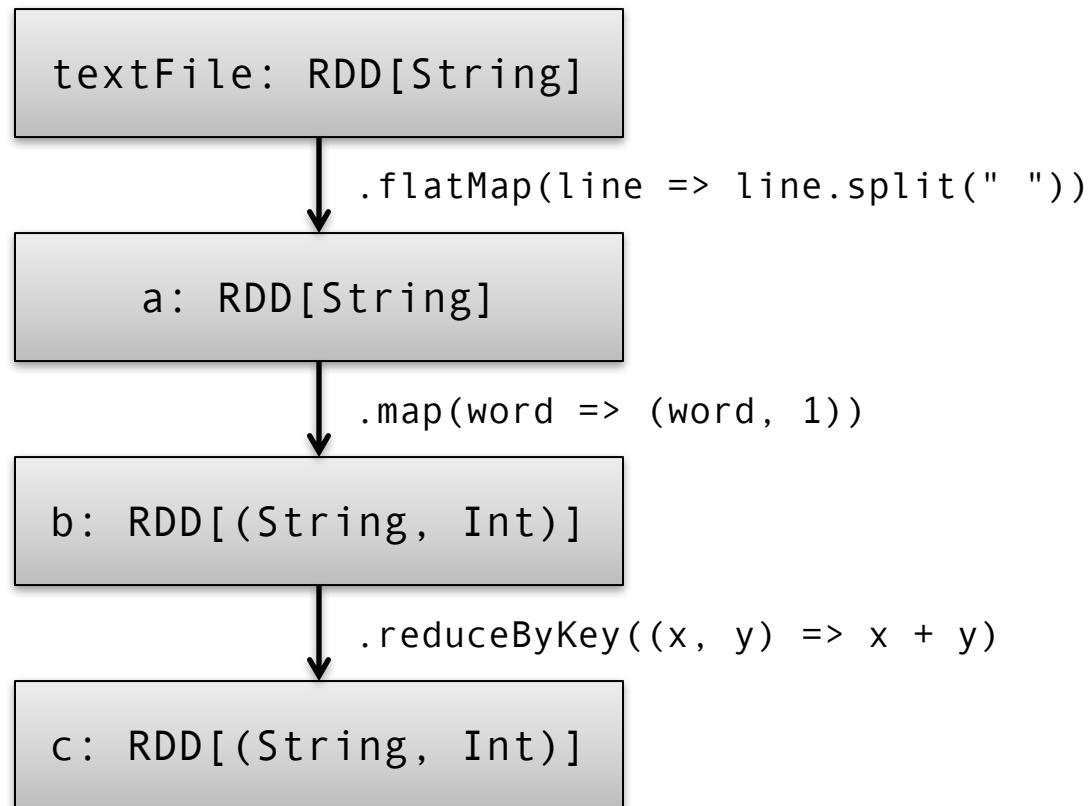
```
c.saveAsTextFile(args.output())
```

Action

Transformations

RDDs and Lineage

On HDFS



Action!

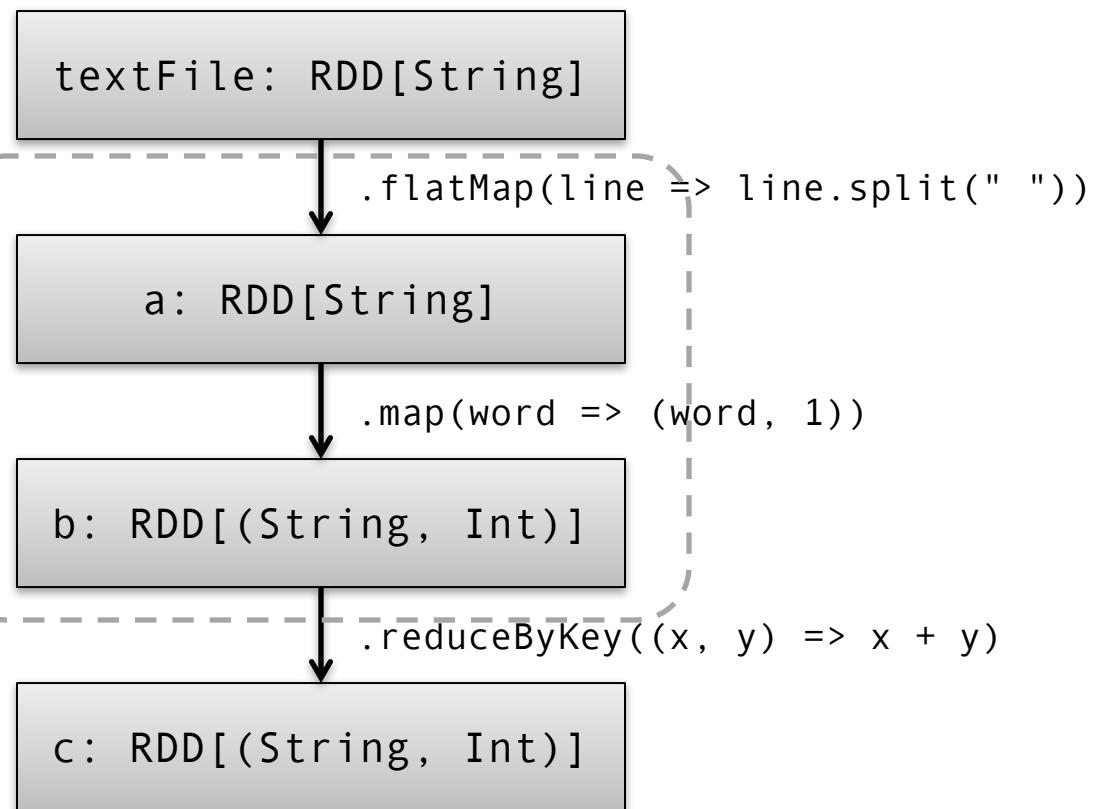
Remember,
transformations are lazy!

RDDs and Optimizations

Lazy evaluation creates optimization opportunities

On HDFS
RDDs don't need
to be materialized!

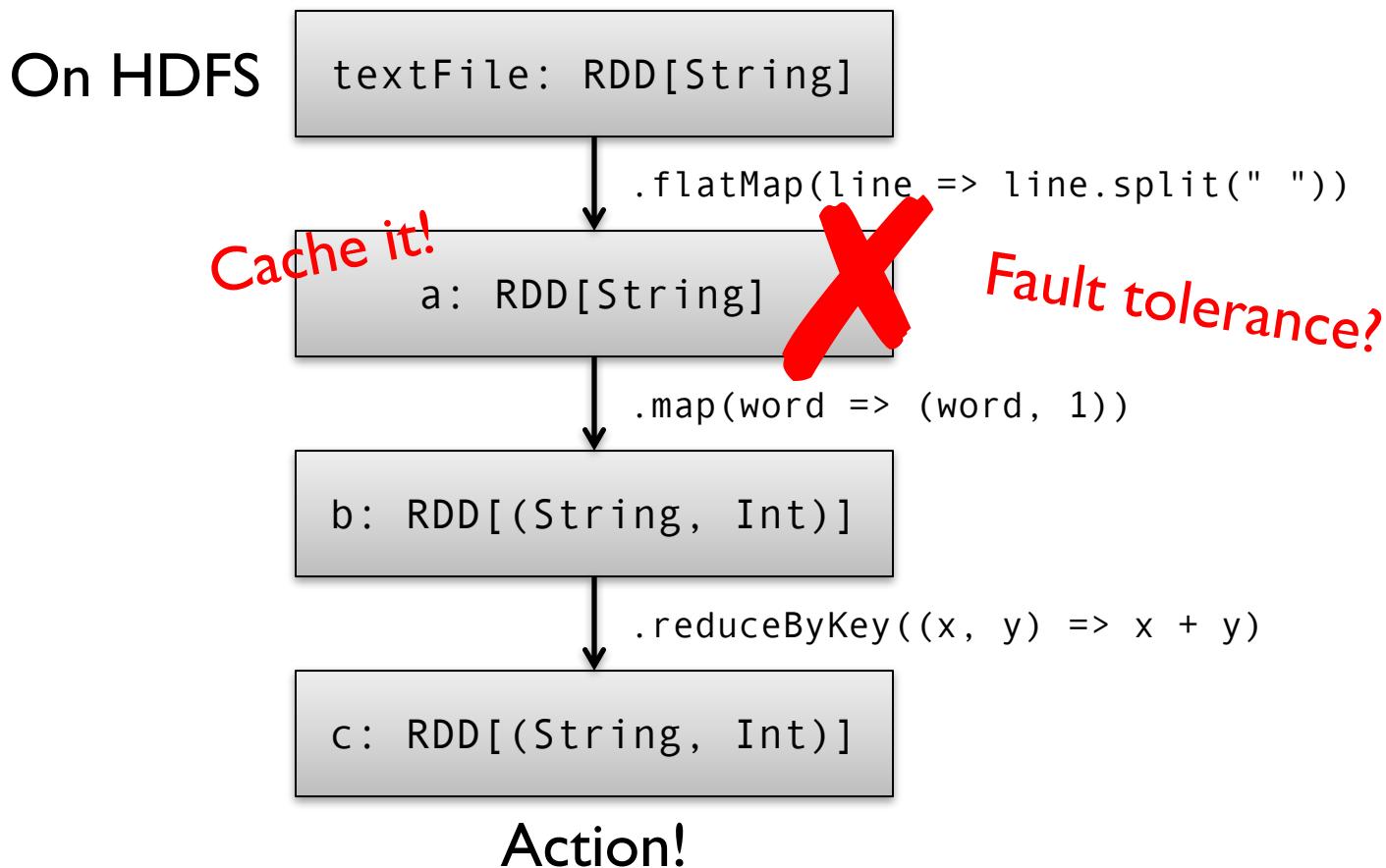
Want MM?



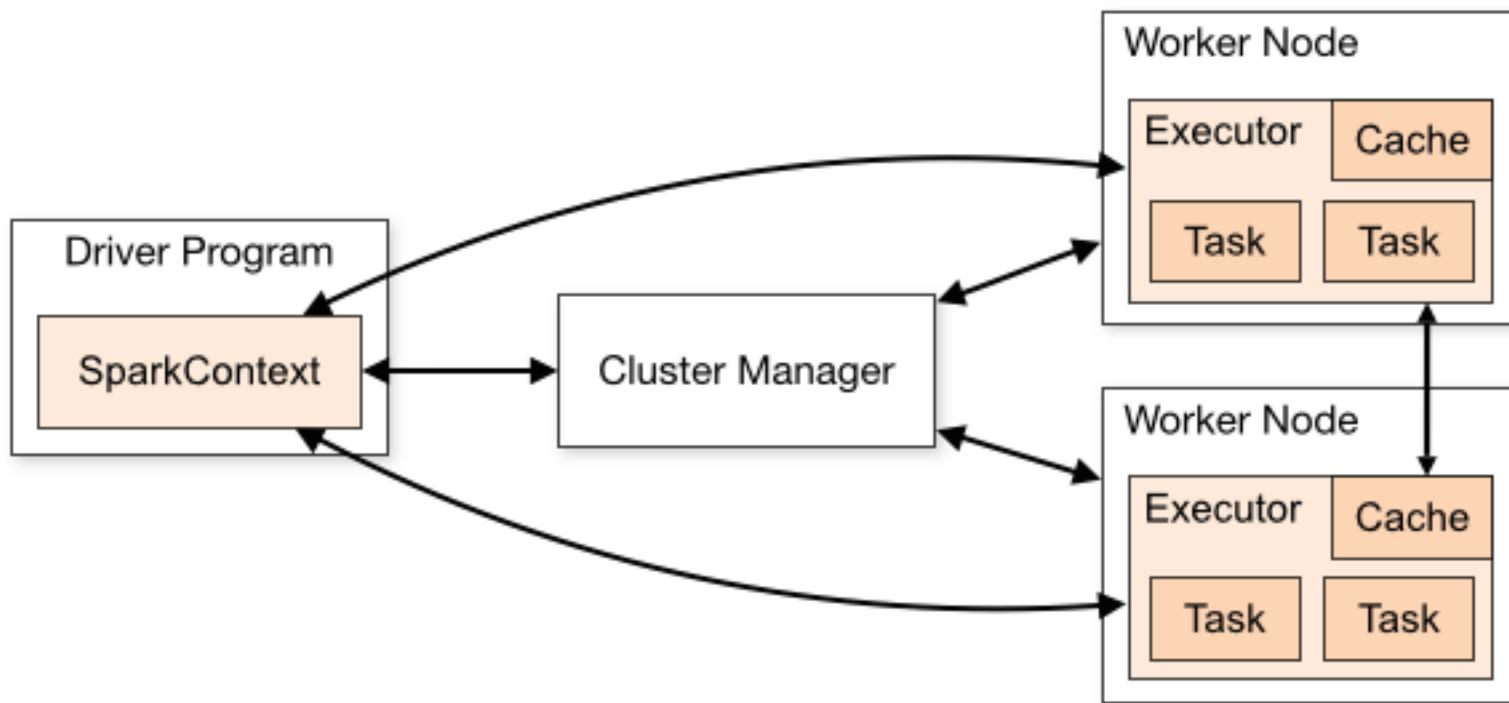
Action!

RDDs and Caching

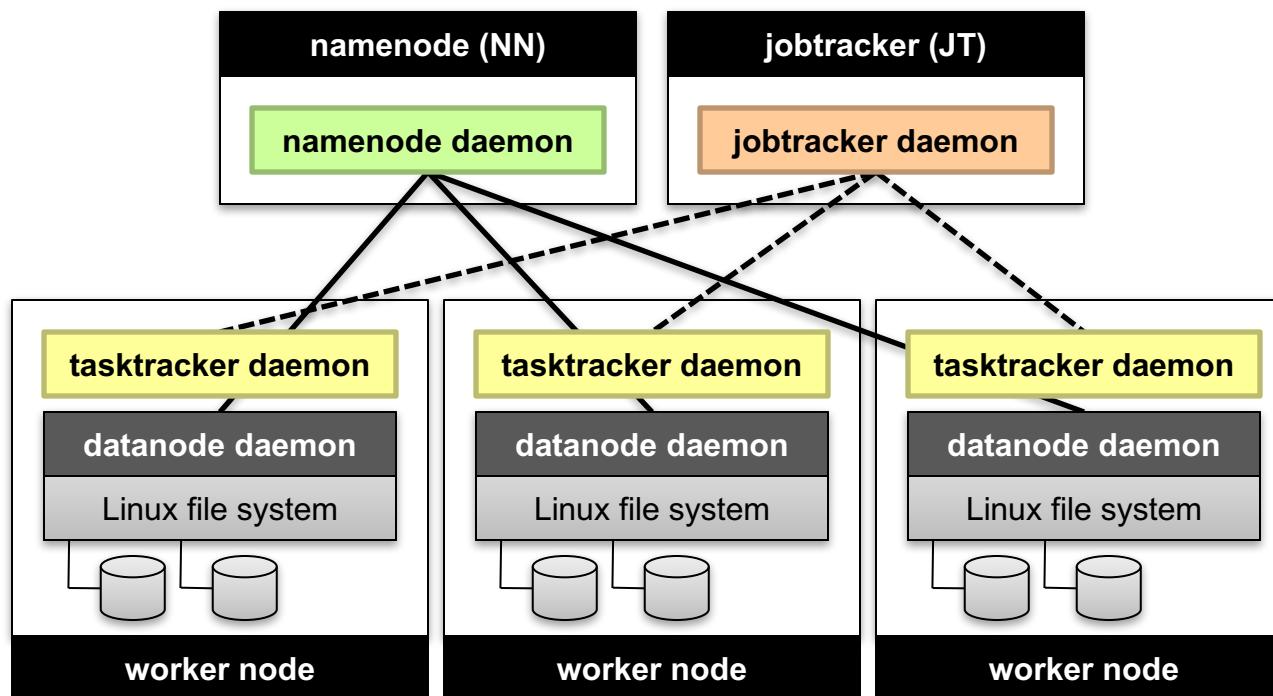
RDDs can be materialized in memory (and on disk)!



Spark Architecture



Hadoop MapReduce Architecture



An Apt Quote

All problems in computer science can be solved
by another level of indirection... Except for the
problem of too many layers of indirection.

- David Wheeler

YARN

Hadoop's (original) limitations:

Can only run MapReduce

What if we want to run other distributed frameworks?

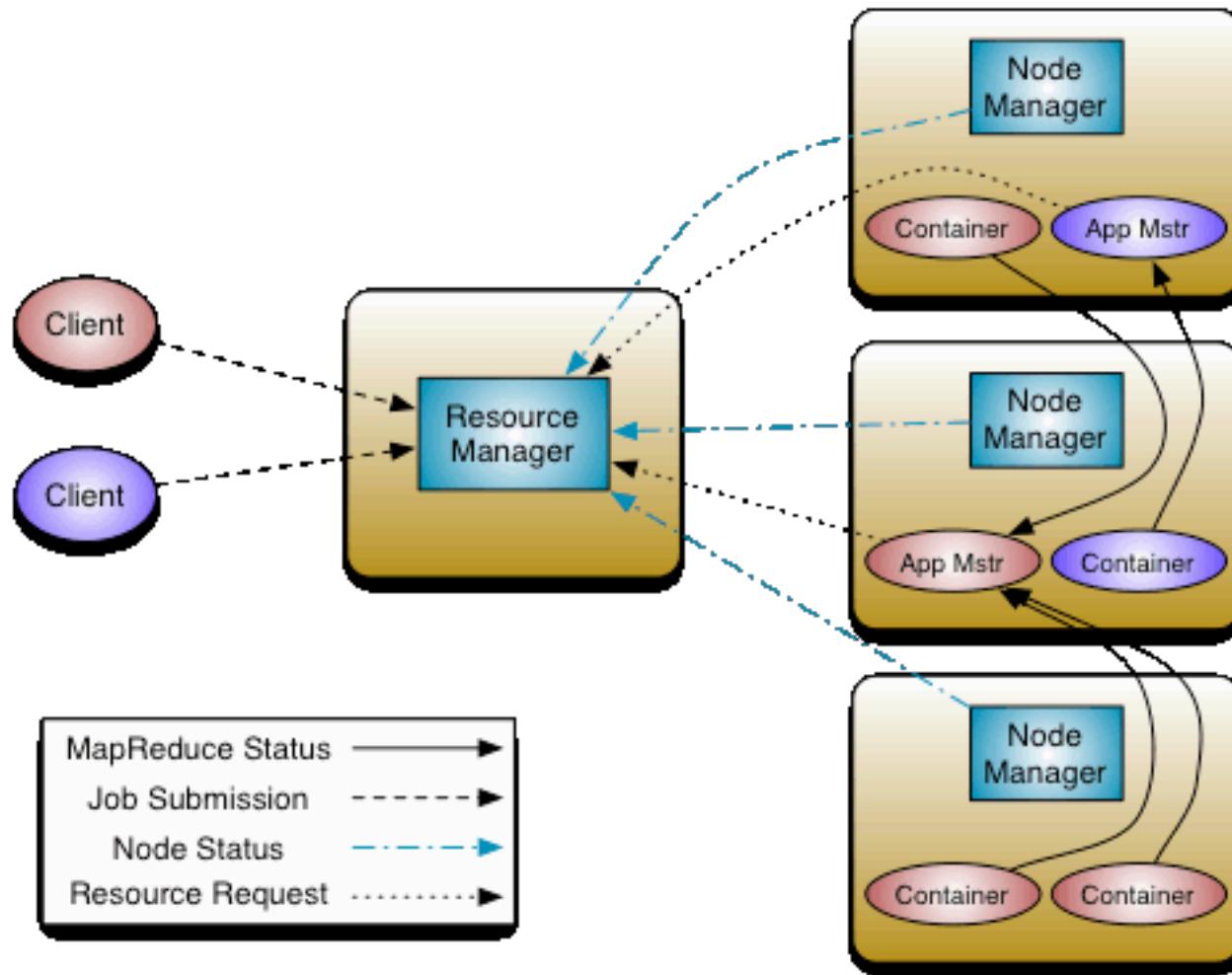
YARN = Yet-Another-Resource-Negotiator

Provides API to develop any generic distributed application

Handles scheduling and resource request

MapReduce (MR2) is one such application in YARN

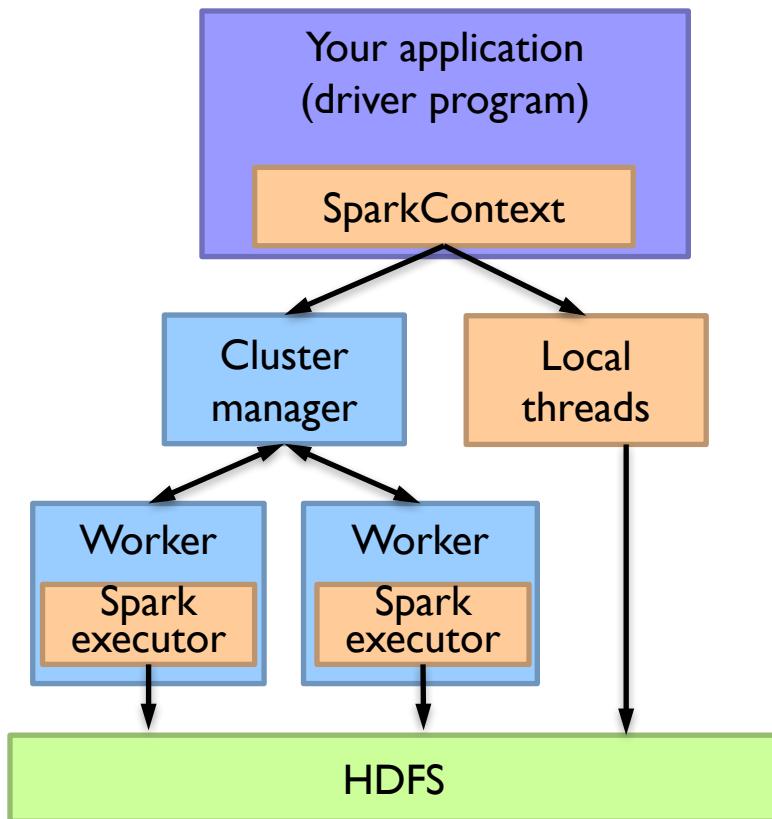
YARN



Spark Programs

Scala, Java, Python, R

spark-shell spark-submit

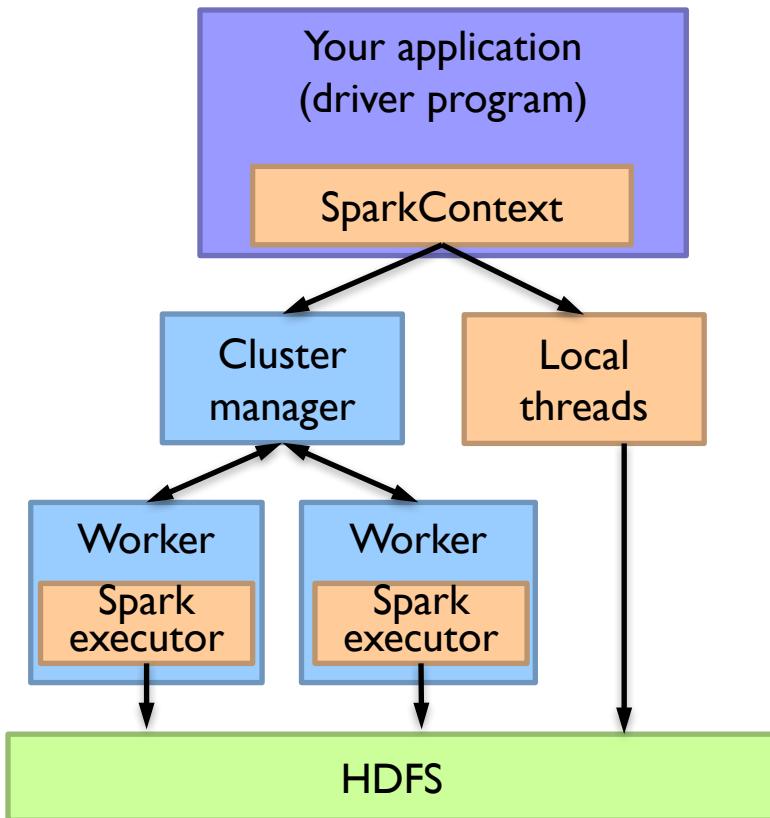


Spark context: tells the framework where to find the cluster

Use the Spark context to create RDDs

Spark Driver

spark-shell spark-submit

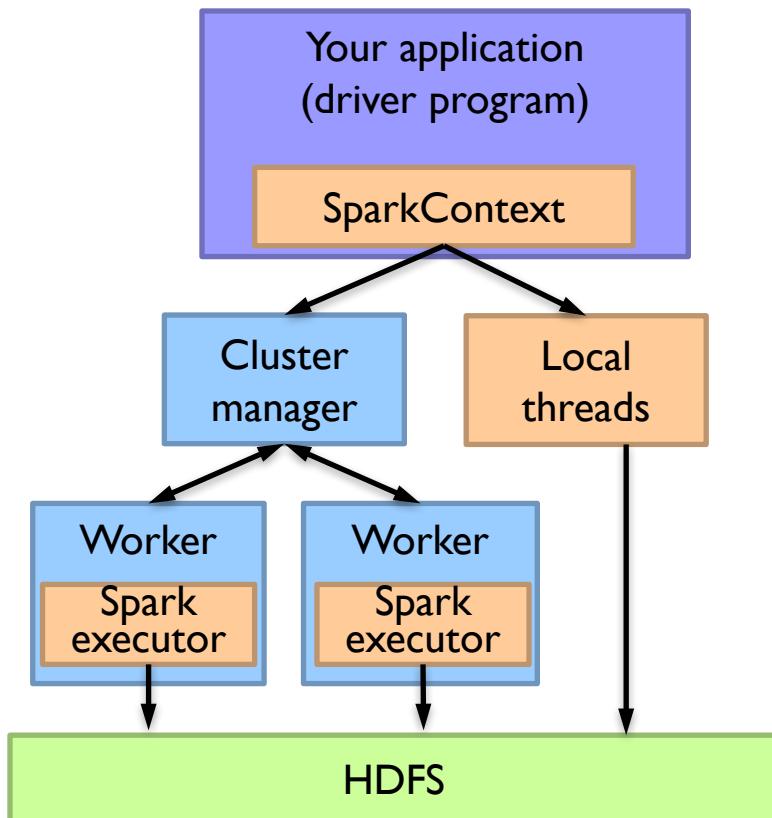


```
val textFile =  
  sc.textFile(args.input())  
  
textFile  
  .flatMap(line => tokenize(line))  
  .map(word => (word, 1))  
  .reduceByKey((x, y) => x + y)  
  .saveAsTextFile(args.output())
```

What's happening
to the functions?

Spark Driver

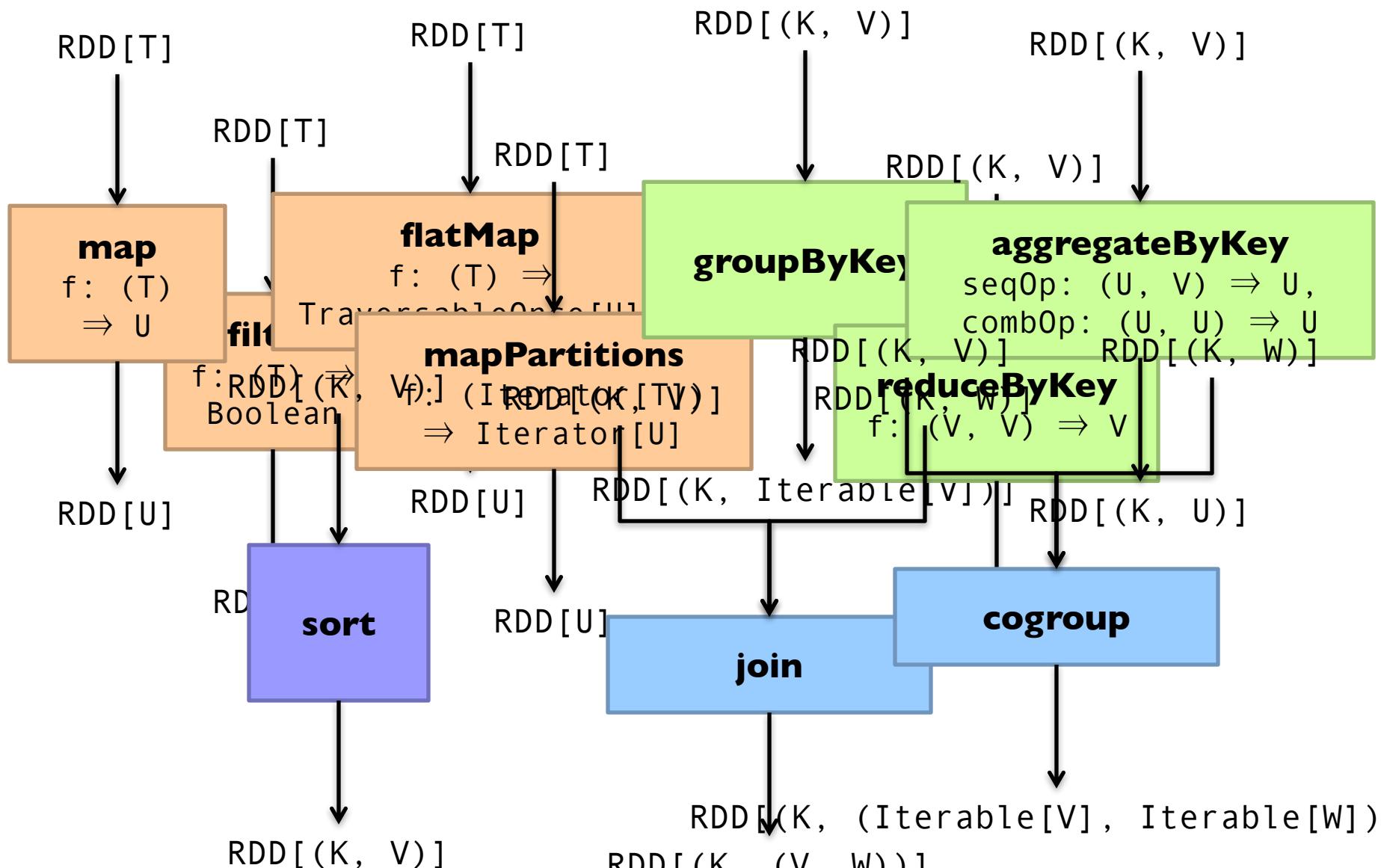
spark-shell spark-submit



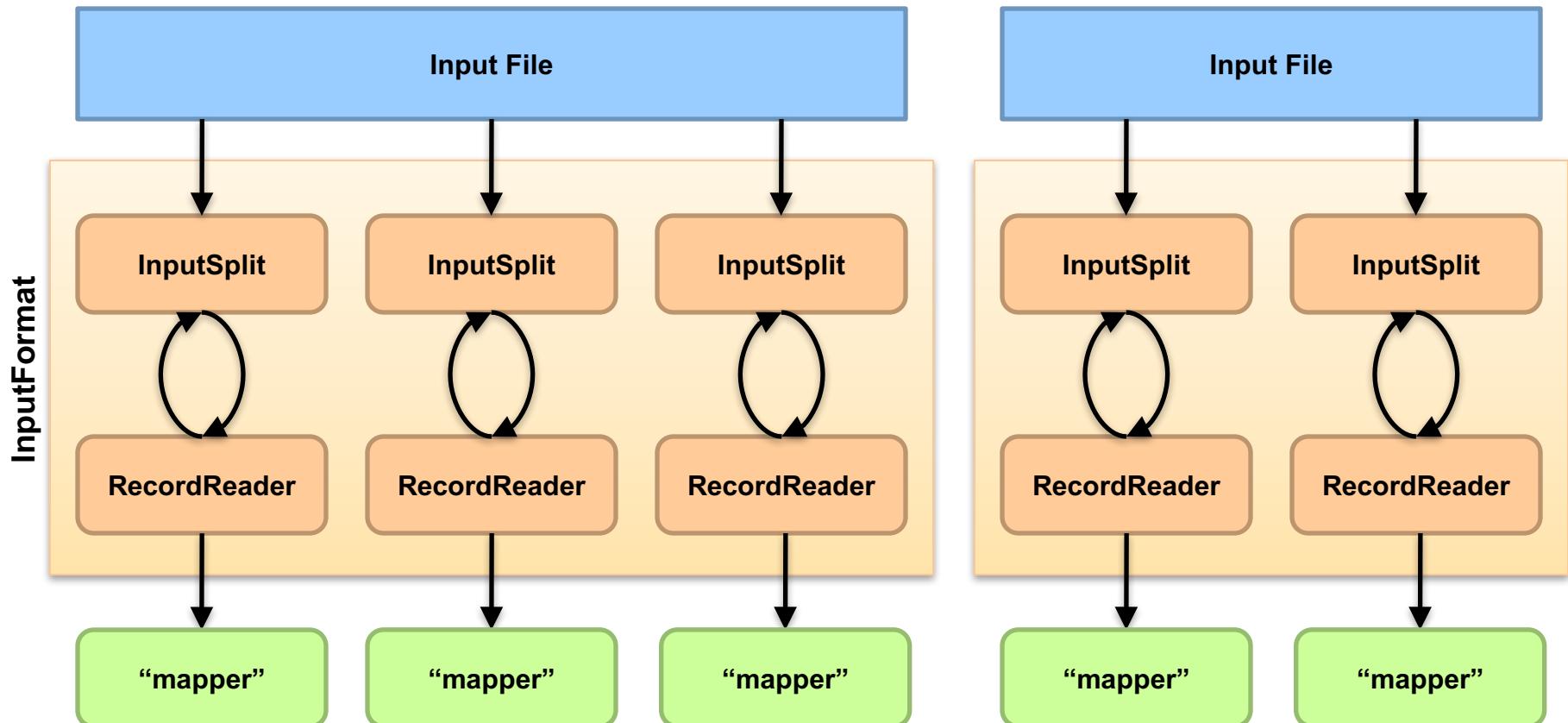
```
val textFile =  
  sc.textFile(args.input())  
  
textFile  
  .flatMap(line => tokenize(line))  
  .map(word => (word, 1))  
  .reduceByKey((x, y) => x + y)  
  .saveAsTextFile(args.output())
```

Note: you can run code “locally”,
integrate cluster-computed values!
Beware of the collect action!

Spark Transformations

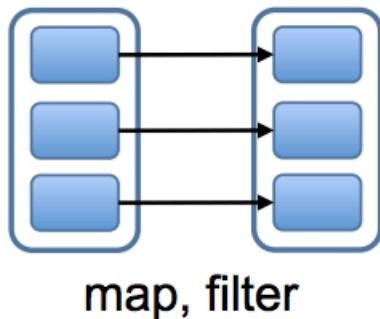


Starting Points

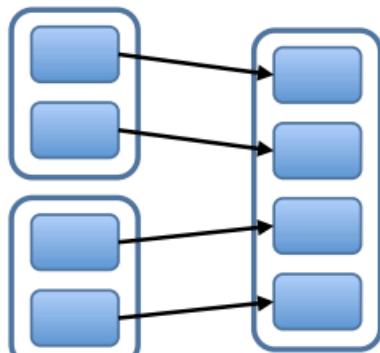


Physical Operators

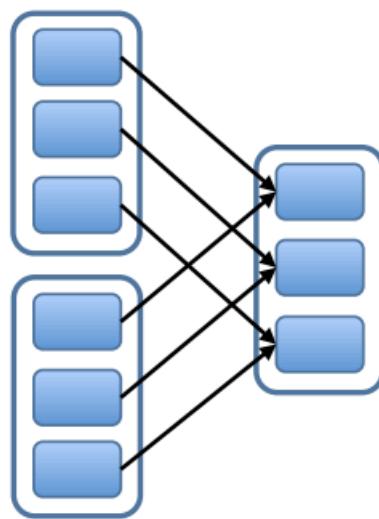
Narrow Dependencies:



map, filter

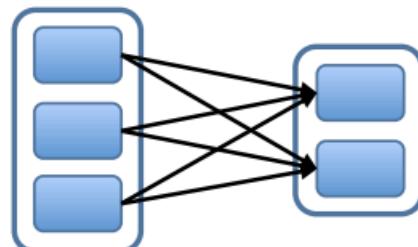


union

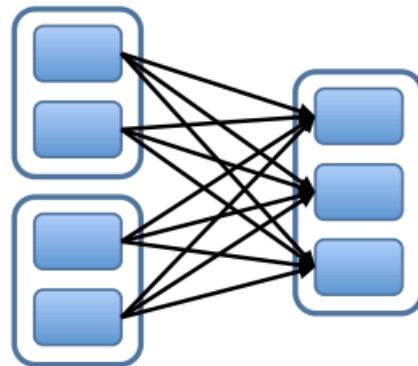


join with inputs
co-partitioned

Wide Dependencies:

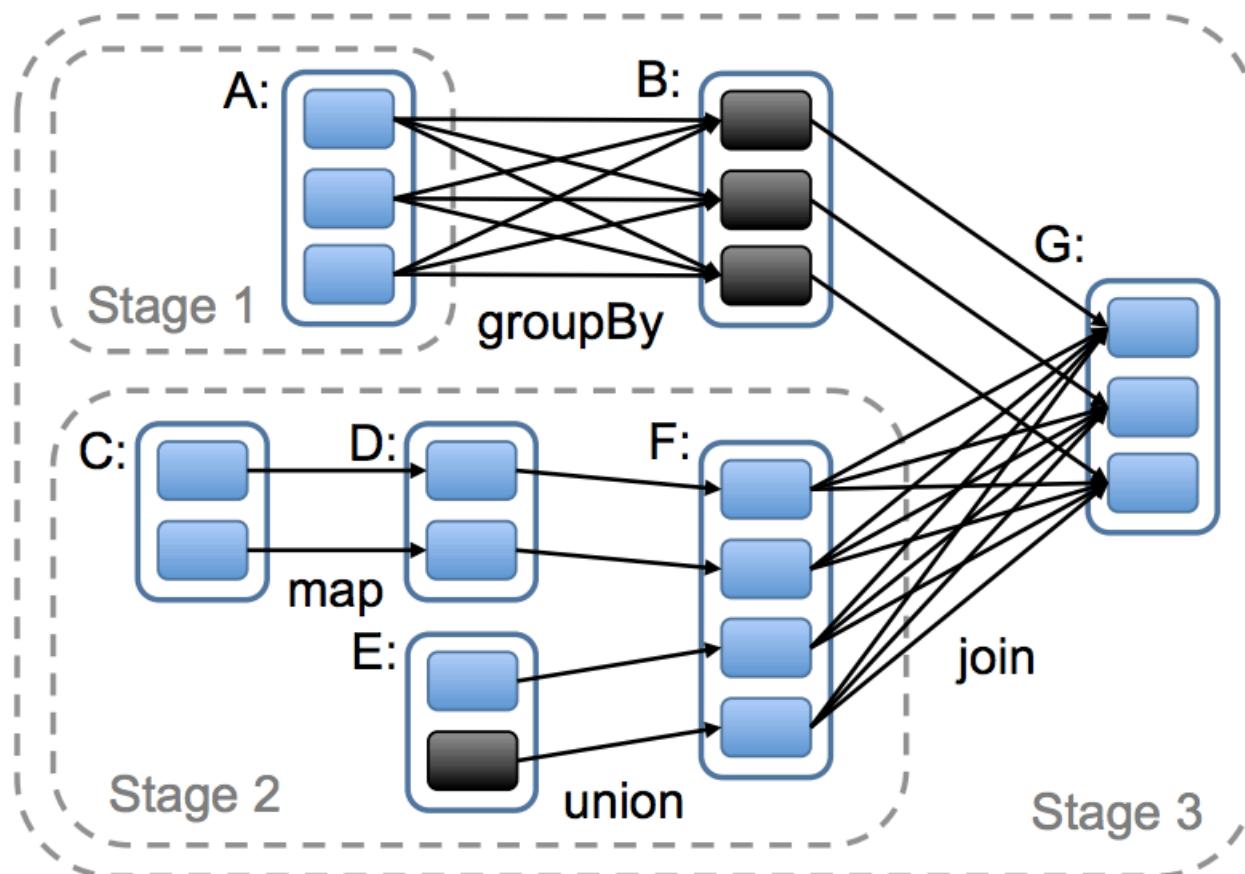


groupByKey



join with inputs not
co-partitioned

Execution Plan

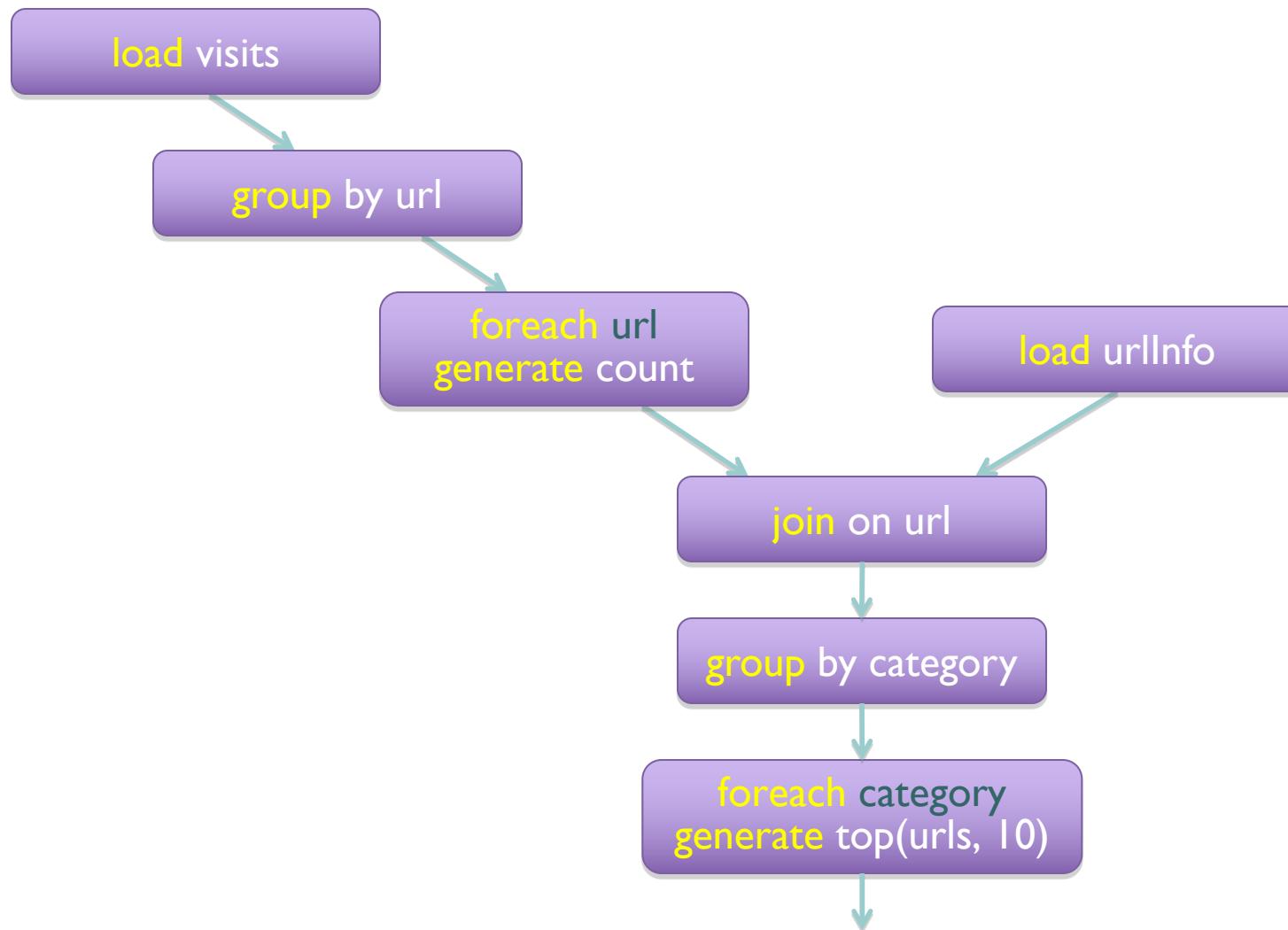


Wait, where have we seen this before?

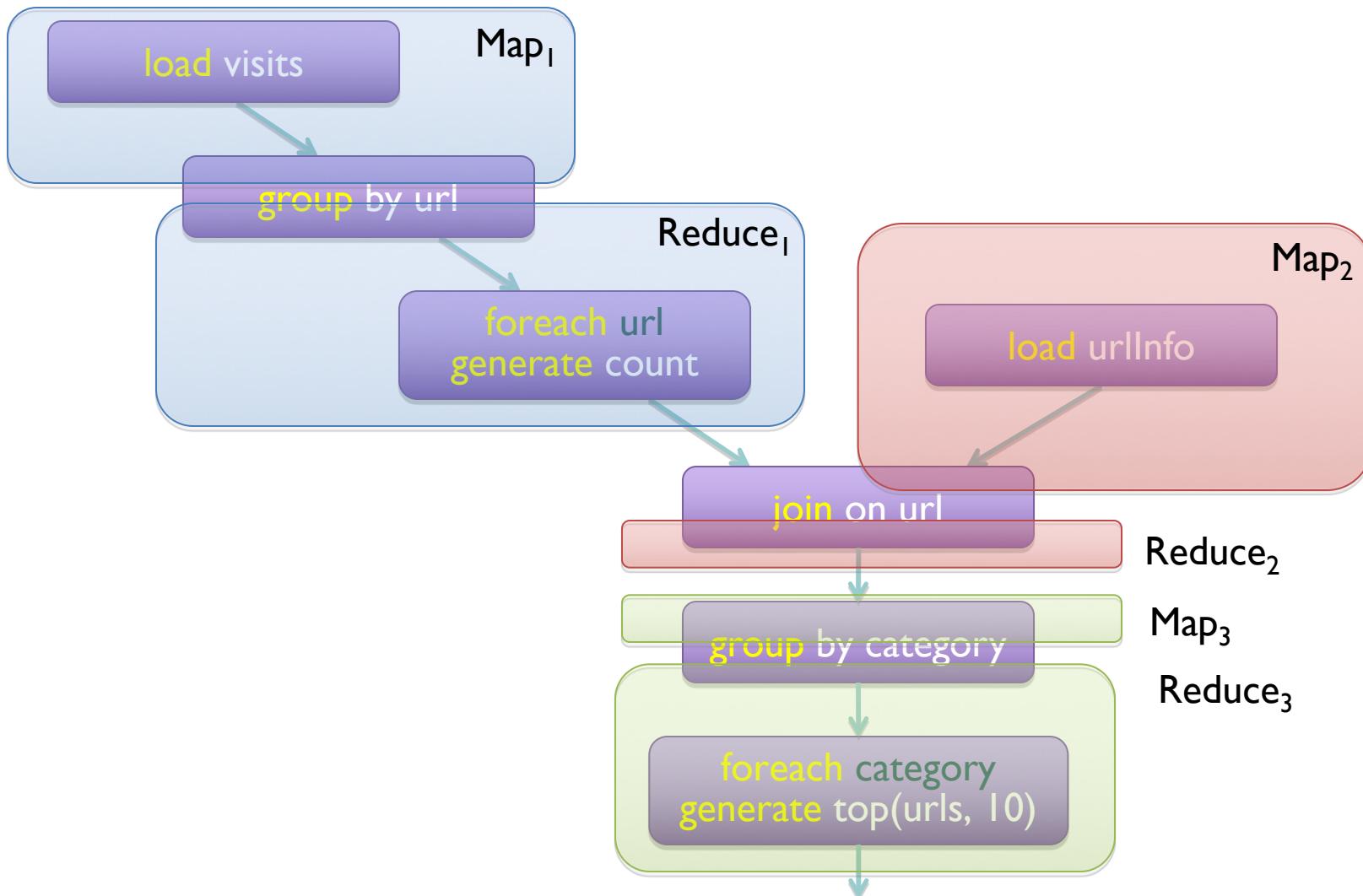
Pig: Example Script

```
visits = load '/data/visits' as (user, url, time);  
gVisits = group visits by url;  
visitCounts = foreach gVisits generate url, count(visits);  
urlInfo = load '/data/urlInfo' as (url, category, pRank);  
visitCounts = join visitCounts by url, urlInfo by url;  
gCategories = group visitCounts by category;  
topUrls = foreach gCategories generate top(visitCounts,10);  
  
store topUrls into '/data/topUrls';
```

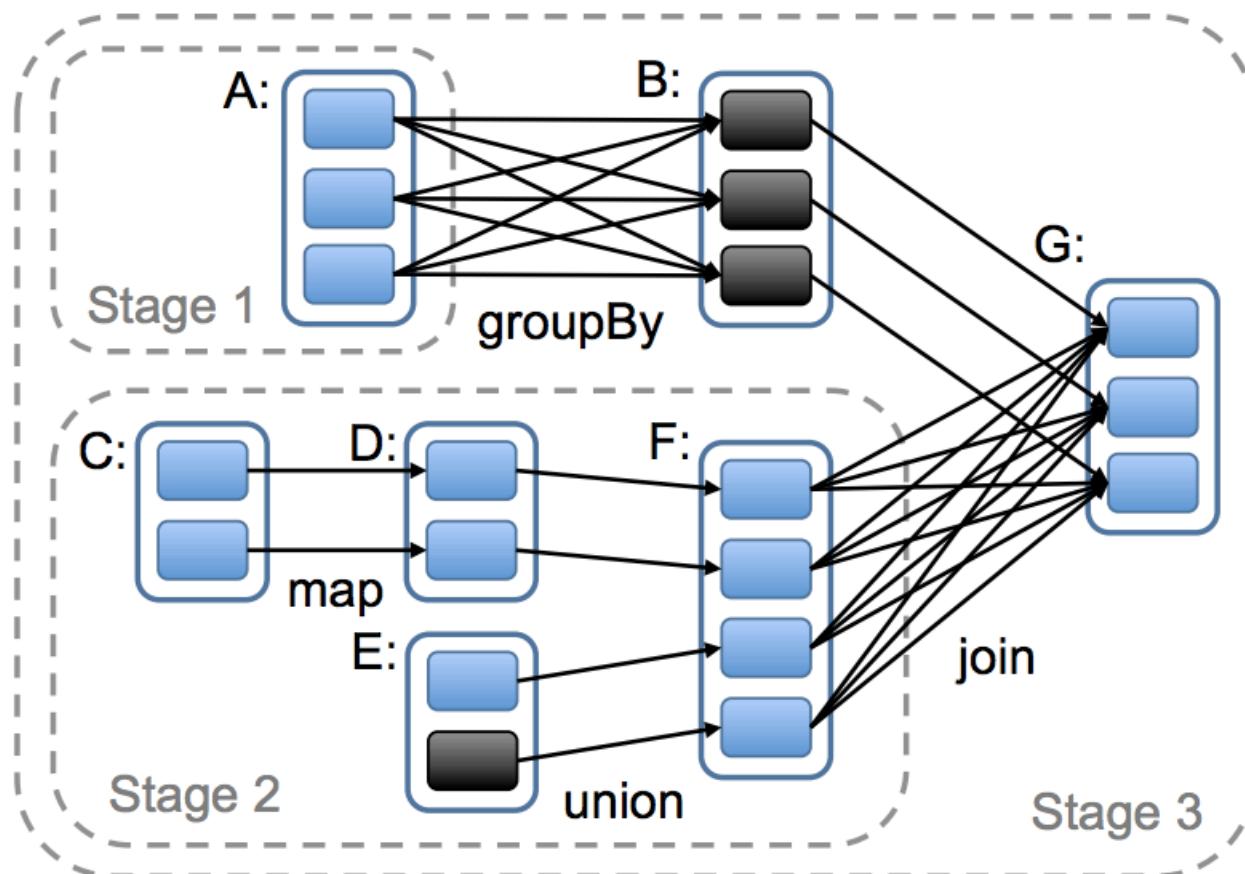
Pig Query Plan



Pig: MapReduce Execution

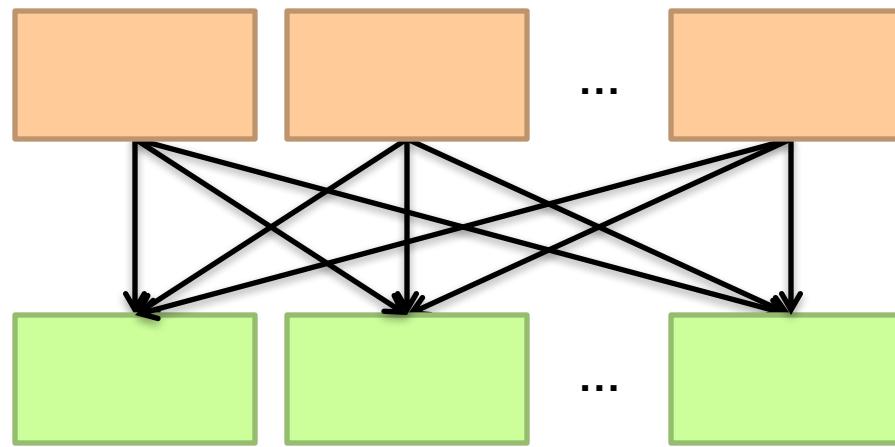


Execution Plan



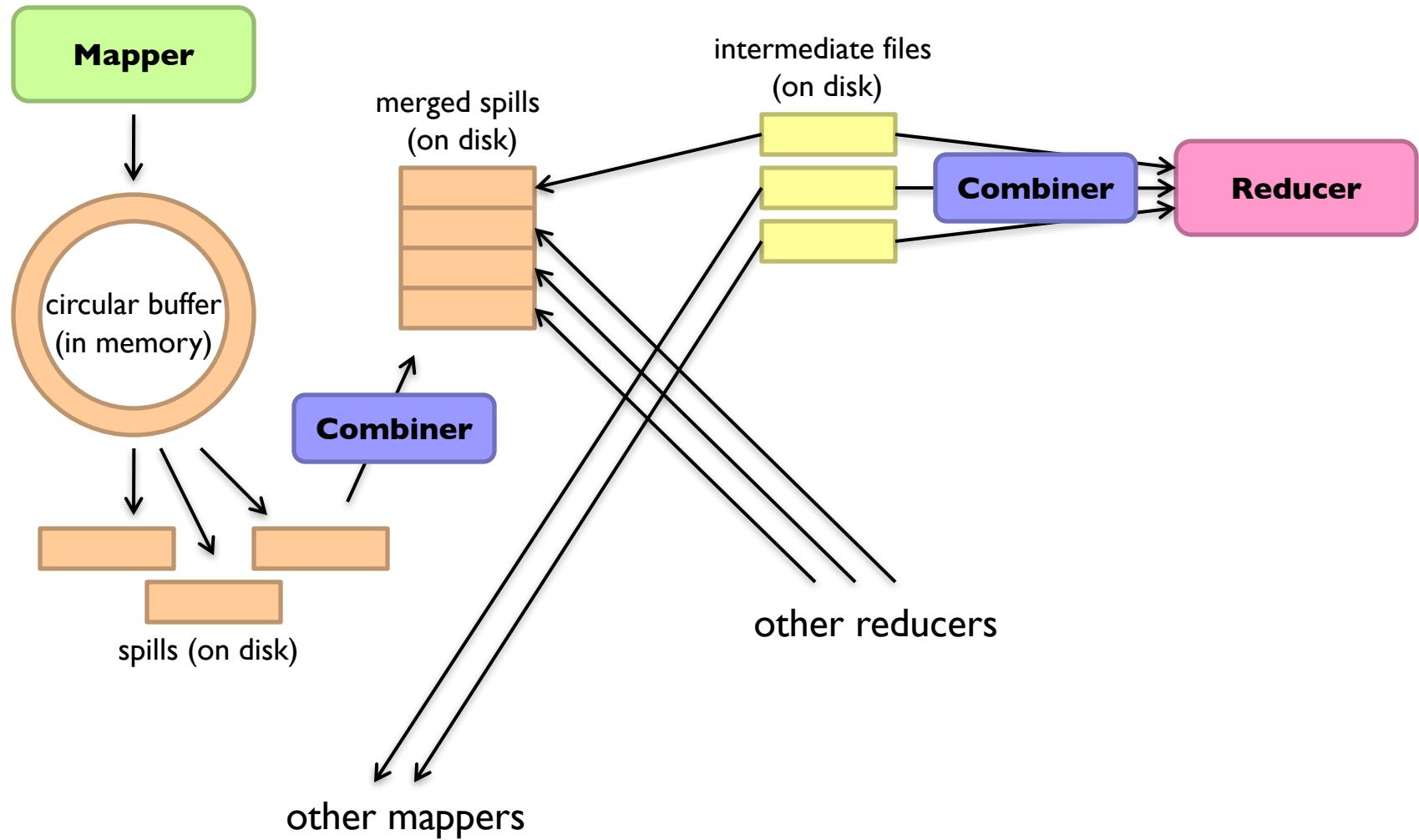
Kinda like a sequence of MapReduce jobs?

Can't avoid this!



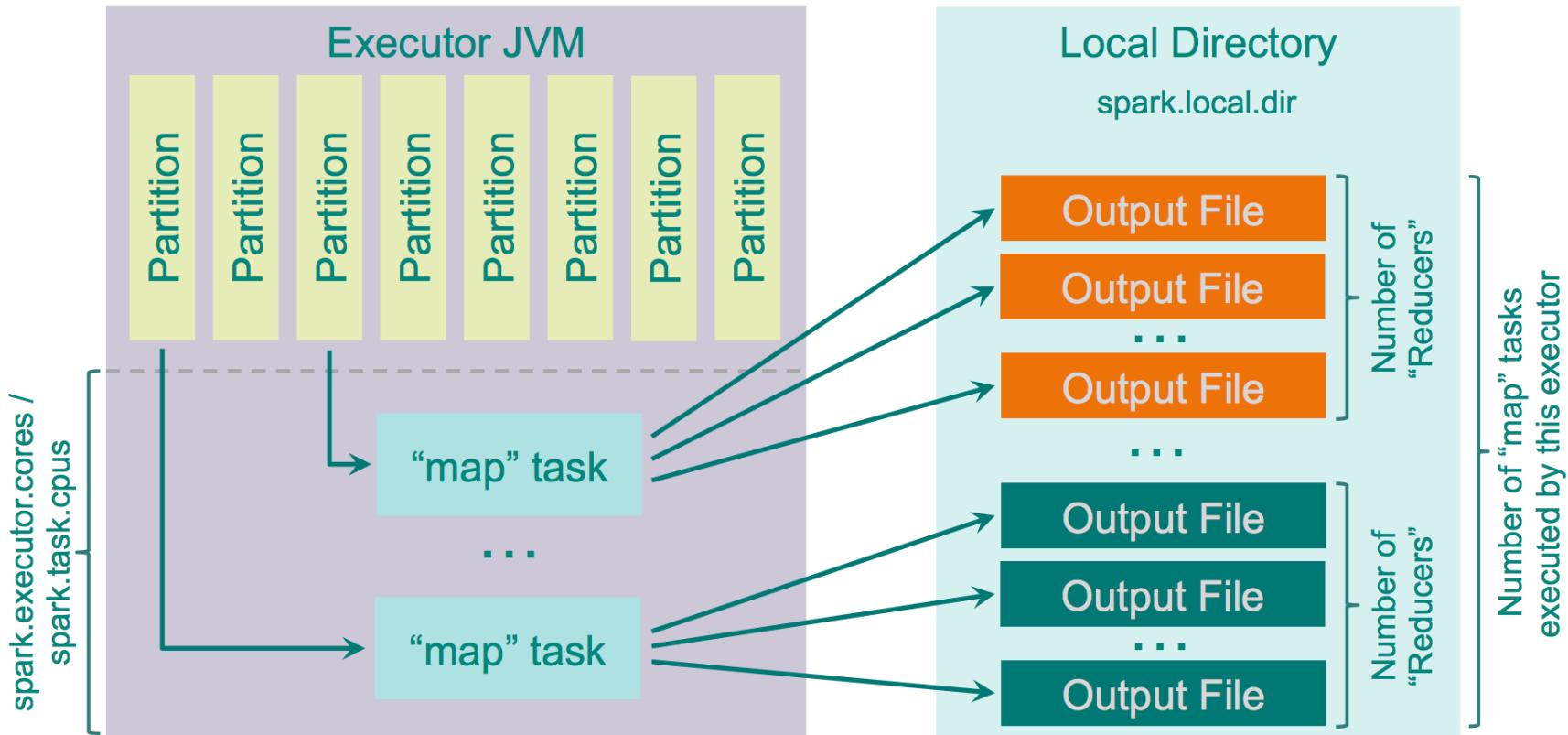
But, what's the major difference?

Remember this?



Spark Shuffle Implementations

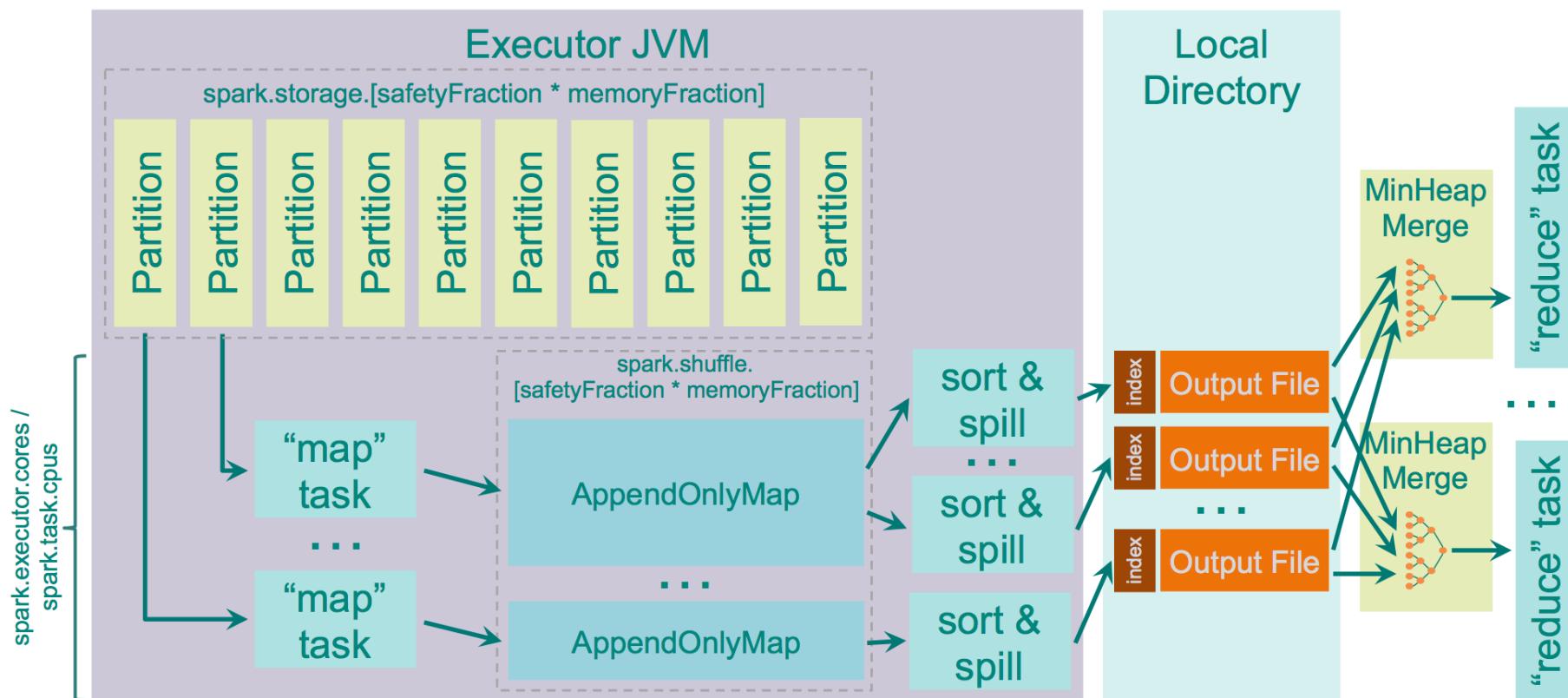
Hash shuffle



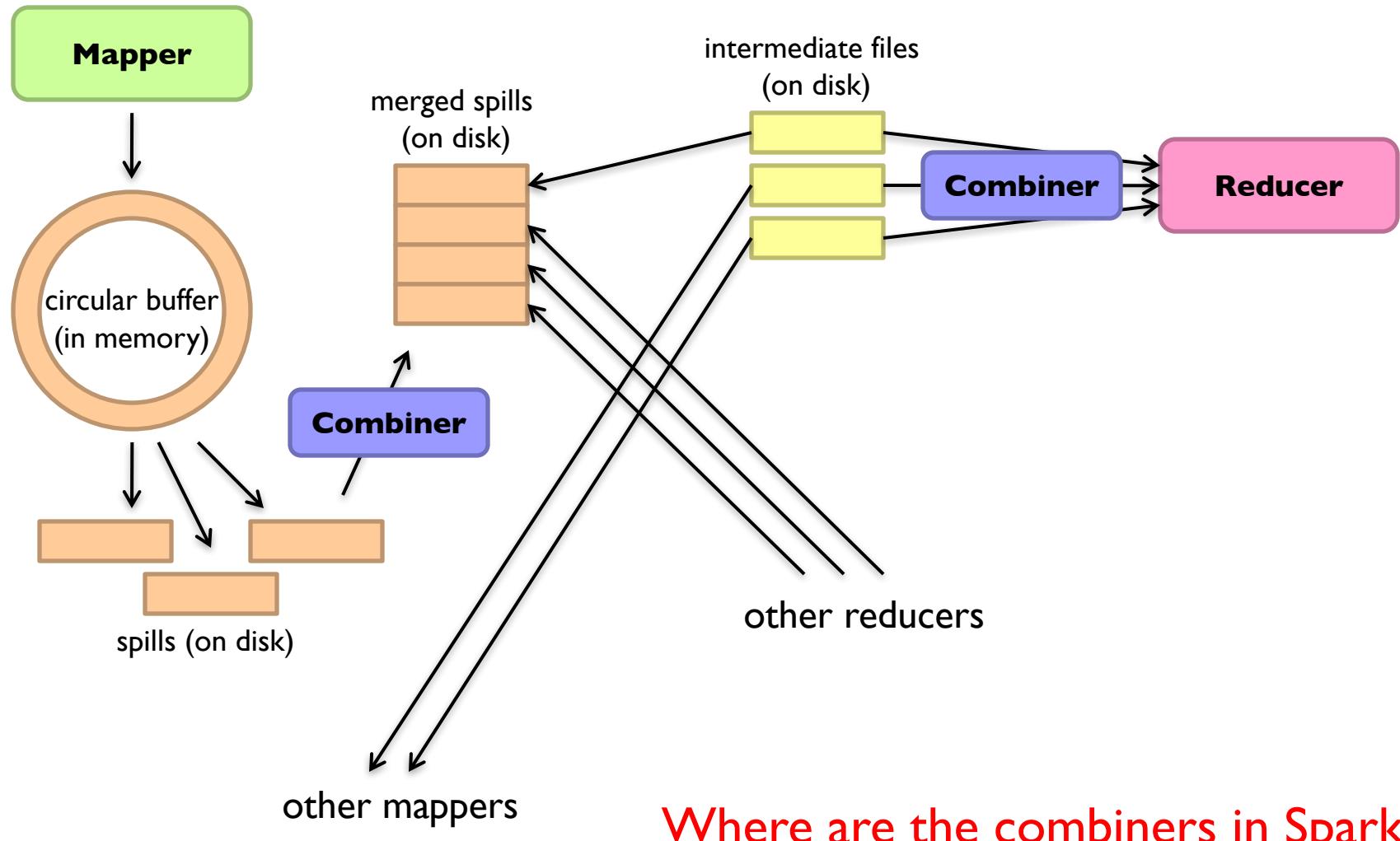
What happened to sorting?

Spark Shuffle Implementations

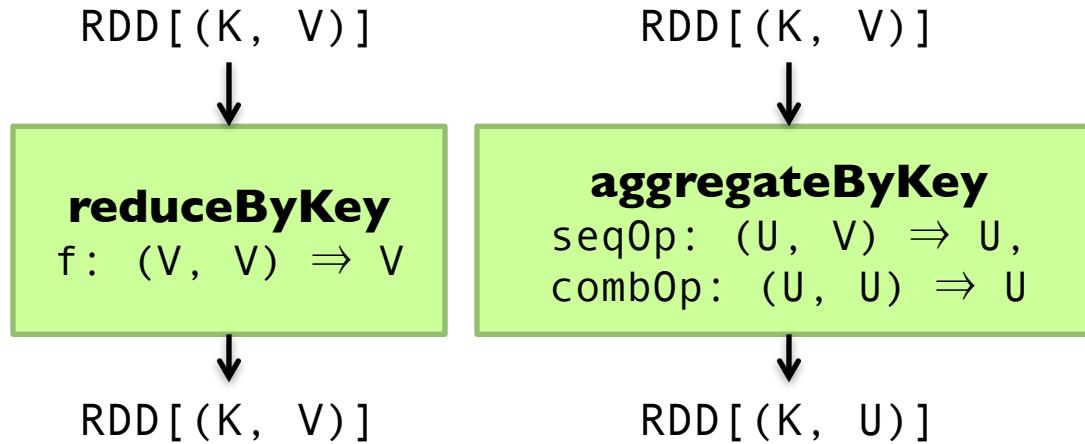
Sort shuffle



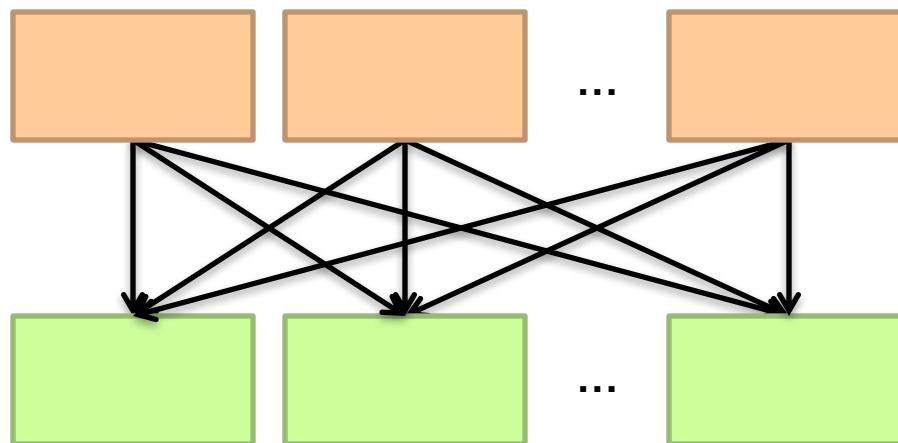
Remember this?



Reduce-like Operations



What happened to combiners?



Spark #wins

Richer operators

RDD abstraction supports
optimizations (pipelining, caching, etc.)

Scala, Java, Python, R, bindings

Spark #wins

The screenshot shows a Databricks notebook interface with the following details:

- Title Bar:** "Quick Start Using Scala - Data" and "Jimmy".
- URL:** https://cdn2.hubspot.net/hubfs/438089/notebooks/Quick_Start/Quick_Start_Using_Scala.html
- Header:** "databricks" logo, "Quick Start Using Scala (Scala)", and "Import Notebook" button.
- Code and Output:**
 - Code cell:

```
> // Take a look at the file system
display(dbutils.fs.ls("/databricks-datasets/samples/docs/"))
```
 - Output:

path	name	size
dbfs:/databricks-datasets/samples/docs/README.md	README.md	3137

[Download](#)
 - Code cell:

```
> // Setup the textFile RDD to read the README.md file
// Note this is lazy
val textFile = sc.textFile("/databricks-datasets/samples/docs/README.md")
```
 - Output:

```
textFile: org.apache.spark.rdd.RDD[String] = /databricks-datasets/samples/docs/README.md MapPartitionsRDD[1873222] at textFile at <console>:34
```
 - Text block: "RDDs have **actions**, which return values, and **transformations**, which return pointers to new RDDs."
 - Code cell:

```
> // When performing an action (like a count) this is when the textFile is read and aggregate calculated
// Click on [View] to see the stages and executors
textFile.count()
```
 - Output:

```
res2: Long = 65
```
- Section Header:** "Scala Count (Jobs)"
- Navigation Bar:** "Jobs" (selected), "Stages", "Storage", "Environment", "Executors", "SQL", "JDBC/ODBC Server".
- Page Footer:** "Total jobs: 1, total tasks: 0, total partitions: 0".

Spark #lose

Java serialization (w/ Kryo optimizations)
Scala: poor support for primitives



Algorithm design, redux



Two superpowers:

Associativity
Commutativity
(sorting)

What follows... very basic category theory...

The Power of Associativity

You can put parentheses where ever you want!

$$(v_1 \oplus v_2 \oplus v_3) \oplus (v_4 \oplus v_5 \oplus v_6 \oplus v_7) \oplus (v_8 \oplus v_9)$$

$$(v_1 \oplus v_2) \oplus (v_3 \oplus v_4 \oplus v_5) \oplus (v_6 \oplus v_7 \oplus v_8 \oplus v_9)$$

$$(v_1 \oplus v_2 \oplus (v_3 \oplus v_4 \oplus v_5)) \oplus (v_6 \oplus v_7 \oplus v_8 \oplus v_9)$$

The Power of Commutativity

You can swap order of operands however you want!

$$(v_1 \oplus v_2 \oplus v_3) \oplus (v_4 \oplus v_5 \oplus v_6 \oplus v_7) \oplus (v_8 \oplus v_9)$$

$$(v_4 \oplus v_5 \oplus v_6 \oplus v_7) \oplus (v_1 \oplus v_2 \oplus v_3) \oplus (v_8 \oplus v_9)$$

$$(v_8 \oplus v_9) \oplus (v_4 \oplus v_5 \oplus v_6 \oplus v_7) \oplus (v_1 \oplus v_2 \oplus v_3)$$

Implications for distributed processing?

You don't know when the tasks begin

You don't know when the tasks end

You don't know when the tasks interrupt each other

You don't know when intermediate data arrive

...

It's okay!

Word Count: Baseline

```
class Mapper {  
    def map(key: Long, value: String) = {  
        for (word <- tokenize(value)) {  
            emit(word, 1)  
        }  
    }  
}  
  
class Reducer {  
    def reduce(key: String, values: Iterable[Int]) = {  
        var sum = 0  
        for (value <- values) {  
            sum += value  
        }  
        emit(key, sum)  
    }  
}
```

Fancy Labels for Simple Concepts...

Semigroup = (M , \oplus)

$\oplus : M \times M \rightarrow M$, s.t., $\forall m_1, m_2, m_3 \in M$

$$(m_1 \oplus m_2) \oplus m_3 = m_1 \oplus (m_2 \oplus m_3)$$

Monoid = Semigroup + identity

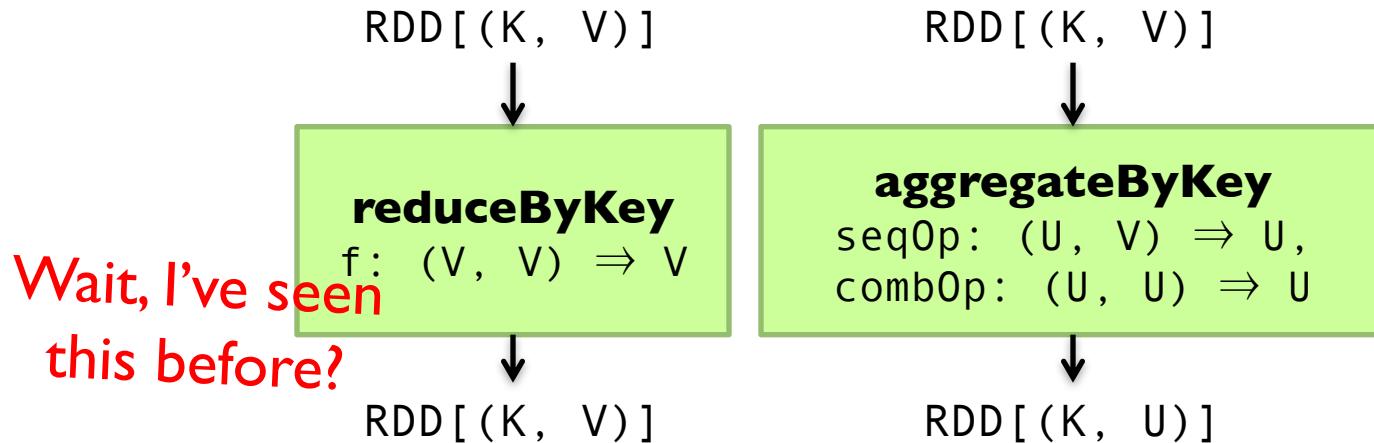
ε s.t., $\varepsilon \oplus m = m \oplus \varepsilon = m$, $\forall m \in M$

Commutative Monoid = Monoid + commutativity

$\forall m_1, m_2 \in M, m_1 \oplus m_2 = m_2 \oplus m_1$

A few examples?
(hint, previous slide!)

Back to these...



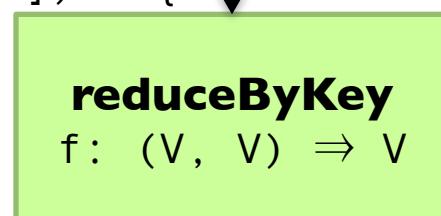
Computing the Mean: Version I

```
class Mapper {  
    def map(key: String, value: Int) = {  
        emit(key, value)  
    }  
}  
  
class Reducer {  
    def reduce(key: String, values: Iterable[Int]) {  
        for (value <- values) {  
            sum += value  
            cnt += 1  
        }  
        emit(key, sum/cnt)  
    }  
}
```

Computing the Mean: Version 3

```
class Mapper {  
    def map(key: String, value: Int) =  
        context.write(key, (value, 1))  
}  
class Combiner {  
    def reduce(key: String, values: Iterable[Pair]) = {  
        for ((s, c) <- values) {  
            sum += s  
            cnt += c  
        }  
        emit(key, (sum, cnt))  
    }  
}  
class Reducer {  
    def reduce(key: String, values: Iterable[Pair]) = {  
        for ((s, c) <- values) {  
            sum += s  
            cnt += c  
        }  
        emit(key, sum/cnt)  
    }  
}
```

Wait, I've seen
this before!

RDD[(K, V)]

↓
reduceByKey
 $f: (V, V) \Rightarrow V$
↓
RDD[(K, V)]

Co-occurrence Matrix: Stripes

```
class Mapper {  
    def map(key: Long, value: String) = {  
        for (u <- tokenize(value)) {  
            val map = new Map()  
            for (v <- neighbors(u)) {  
                map(v) += 1  
            }  
            emit(u, map)  
        }  
    }  
}
```

Wait, I've seen this before?

```
class Reducer {  
    def reduce(key: String, values: Iterable[Map]) = {  
        val map = new Map()  
        for (value <- values) {  
            map += value  
        }  
        emit(key, map)  
    }  
}
```

The diagram illustrates the data flow between the Mapper and Reducer stages. The Mapper's output is an RDD of (key, Map) pairs. This is passed as the 'values' parameter to the Reducer's 'reduce' method. The Reducer's output is also an RDD of (key, Map) pairs. A green box highlights the 'reduceByKey' operation, which takes a function f: (V, V) => V and processes the values for each key.

RDD[(K, V)]

↓

reduceByKey

f: (V, V) ⇒ V

↓

RDD[(K, V)]

Computing the Mean: Version 2

```
class Mapper {  
    def map(key: String, value: Int) =  
        context.write(key, value)  
}  
class Combiner {  
    def reduce(key: String, values: Iterable[Int]) = {  
        for (value <- values) {  
            sum += value  
            cnt += 1  
        }  
        emit(key, (sum, cnt))  
    }  
}  
class Reducer {  
    def reduce(key: String, values: Iterable[Pair]) {  
        for ((s, c) <- values) {  
            sum += s  
            cnt += c  
        }  
        emit(key, sum/cnt)  
    }  
}
```

RDD[(K, V)]

\Downarrow

aggregateByKey

seqOp: $(U, V) \Rightarrow U$,
combOp: $(U, U) \Rightarrow U$

\Downarrow

RDD[(K, U)]

Synchronization: Pairs vs. Stripes

Approach 1: turn synchronization into an ordering problem

Sort keys into correct order of computation

Partition key space so each reducer receives appropriate set of partial results

Hold state in reducer across multiple key-value pairs to perform computation

Illustrated by the “pairs” approach

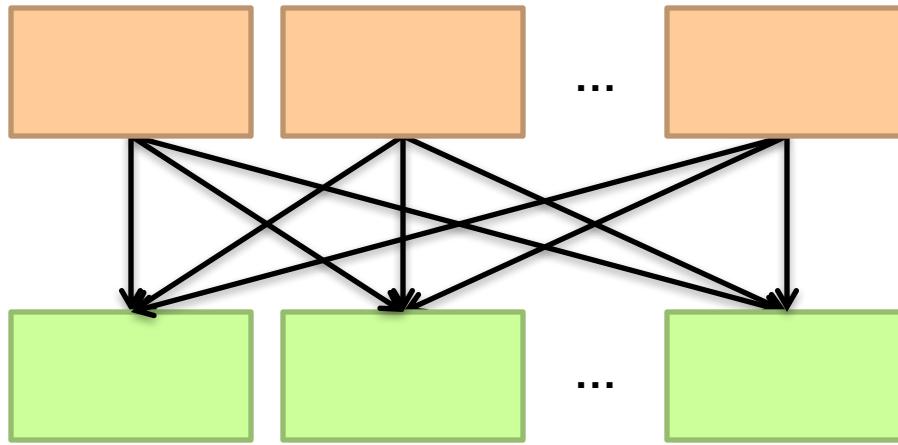
Approach 2: data structures that bring partial results together

Each reducer receives all the data it needs to complete the computation

Illustrated by the “stripes” approach

Commutative monoids!

Because you can't avoid this...



But commutative monoids help

Synchronization: Pairs vs. Stripes

Approach 1: turn synchronization into an ordering problem

Sort keys into correct order of computation

Partition key space so each reducer receives appropriate set of partial results

Hold state in reducer across multiple key-value pairs to perform computation

Illustrated by the “pairs” approach

What about this?

Approach 2: data structures that bring partial results together

Each reducer receives all the data it needs to complete the computation

Illustrated by the “stripes” approach

Commutative monoids!

$f(B|A)$: “Pairs”

$(a, *) \rightarrow 32$

Reducer holds this value in memory

$(a, b_1) \rightarrow 3$

$(a, b_1) \rightarrow 3 / 32$

$(a, b_2) \rightarrow 12$

$(a, b_2) \rightarrow 12 / 32$

$(a, b_3) \rightarrow 7$

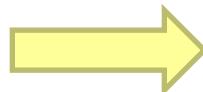
$(a, b_3) \rightarrow 7 / 32$

$(a, b_4) \rightarrow 1$

$(a, b_4) \rightarrow 1 / 32$

...

...



For this to work:

Emit extra $(a, *)$ for every b_n in mapper

Make sure all a 's get sent to same reducer (use partitioner)

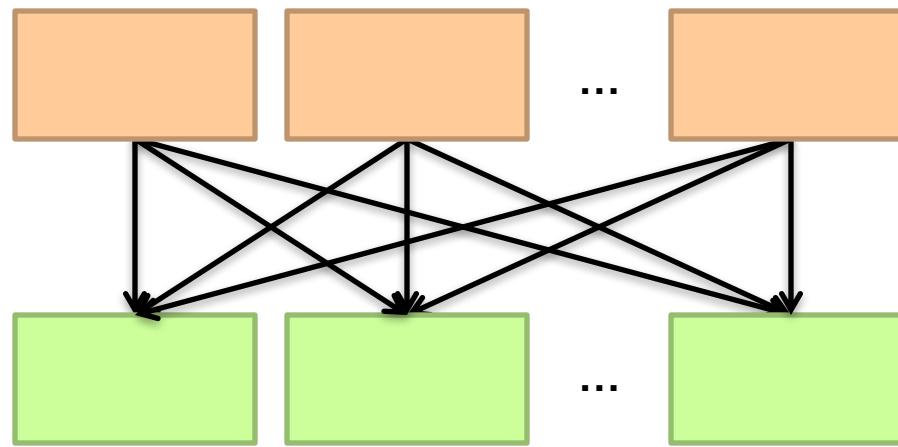
Make sure $(a, *)$ comes first (define sort order)

Hold state in reducer across different key-value pairs



Two superpowers:
Associativity
Commutativity
(sorting)

When you can't “monoidify”



Sequence your computations by sorting

An Apt Quote

All problems in computer science can be solved
by another level of indirection... Except for the
problem of too many layers of indirection.

- David Wheeler

An aerial photograph of a large data center complex during sunset. The sky is a warm orange and yellow. In the foreground, there are several large white buildings, some with flat roofs and others with green roofs. There are also numerous white cylindrical storage tanks arranged in rows. A network of roads and parking lots connects the buildings. In the background, there are more buildings, a highway with traffic, and a vast, green, agricultural landscape stretching to the horizon.

The datacenter *is* the computer!
What's the instruction set?
What are the abstractions?

Algorithm design in a nutshell...



Exploit associativity and commutativity
via commutative monoids (if you can)

Exploit framework-based sorting to
sequence computations (if you can't)

A photograph of a traditional Japanese rock garden. In the foreground, a gravel path is raked into fine, parallel lines. Several large, dark, irregular stones are scattered across the garden. A small, shallow pond is visible in the middle ground, surrounded by more stones and some low-lying green plants. In the background, there are more stones, some small trees, and a traditional wooden building with a tiled roof. The overall atmosphere is peaceful and minimalist.

Questions?