



Data-Intensive Distributed Computing

CS 451/651 431/631 (Winter 2018)

Part I: From MapReduce to Spark (1/2)
January 18, 2018

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



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Debugging at Scale

Works on small datasets, won't scale... why?

Memory management issues (buffering and object creation)

- Too much intermediate data

- Mangled input records

Real-world data is messy!

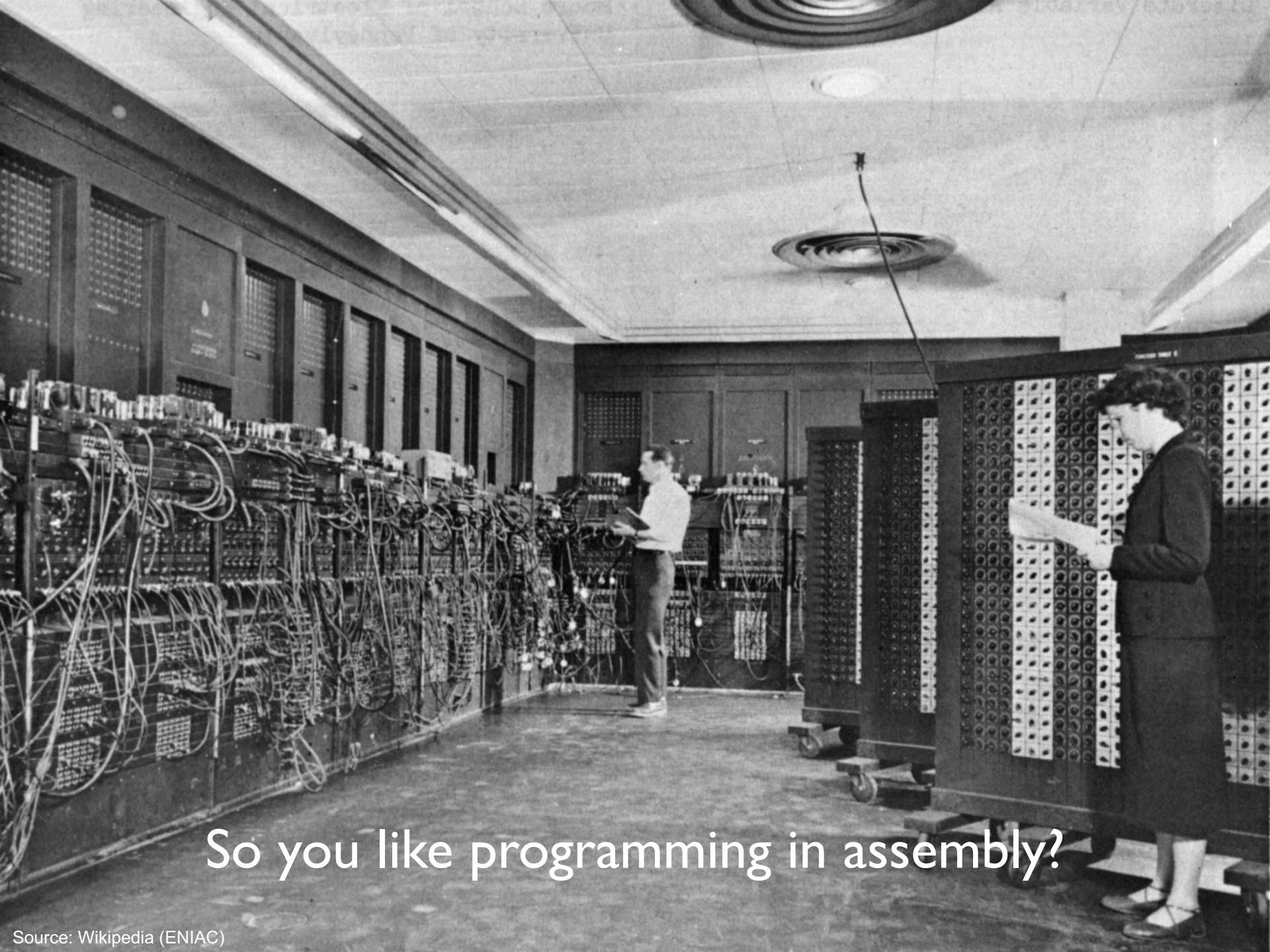
There's no such thing as "consistent data"

- Watch out for corner cases

- Isolate unexpected behavior, bring local

An aerial photograph of a large data center complex during sunset. The sky is a vibrant orange and yellow. In the foreground, there are several large white industrial buildings, parking lots, and rows of white shipping containers. A major highway runs through the middle ground. The background shows a vast, green, agricultural landscape with rolling hills under the setting sun.

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



So you like programming in assembly?



Hadoop is great, but it's really waaaaay too low level!
(circa 2007)

What's the solution?

Design a higher-level language
Write a compiler

Hadoop is great, but it's really waaaaay too low level!
(circa 2007)



What we really need is SQL!



What we really need is a
scripting language!

Answer:



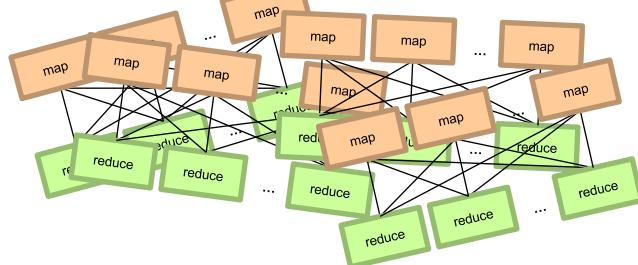
Answer:



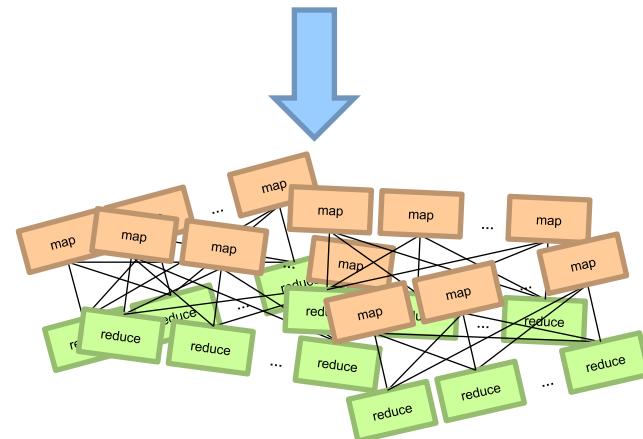


SQL

Aside: Why not just
use a database?



Pig Scripts



Both open-source projects today!

Story for another day....



Jeff Hammerbacher, Information Platforms and the Rise of the Data Scientist.
In, *Beautiful Data*, O'Reilly, 2009.

“On the first day of logging the Facebook clickstream, more than 400 gigabytes of data was collected. The load, index, and aggregation processes for this data set really taxed the Oracle data warehouse. Even after significant tuning, we were unable to aggregate a day of clickstream data in less than 24 hours.”

A large, light-colored pig, possibly a Berkshire or similar breed, is lying on a bed of dry straw. The pig is positioned horizontally across the frame, with its head towards the bottom left and its tail towards the top right. It has a thick, pinkish-brown coat with some darker pigmentation around its ears and tail. The straw is a golden-yellow color and appears to be in a barn or stable setting.

Pig!

Pig: Example

Task: Find the top 10 most visited pages in each category

Visits

User	Url	Time
Amy	cnn.com	8:00
Amy	bbc.com	10:00
Amy	flickr.com	10:05
Fred	cnn.com	12:00



URL Info

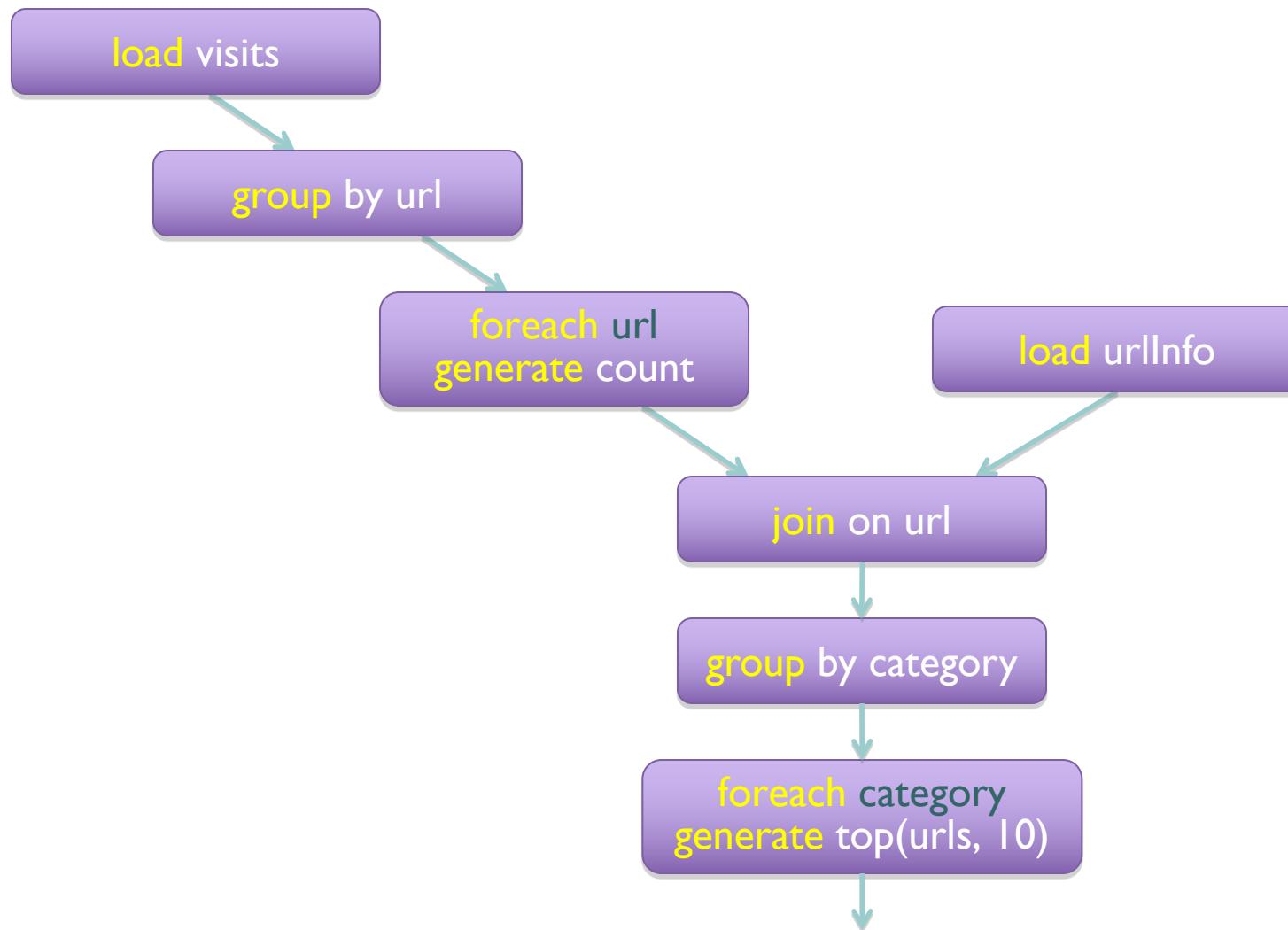
Url	Category	PageRank
cnn.com	News	0.9
bbc.com	News	0.8
flickr.com	Photos	0.7
espn.com	Sports	0.9



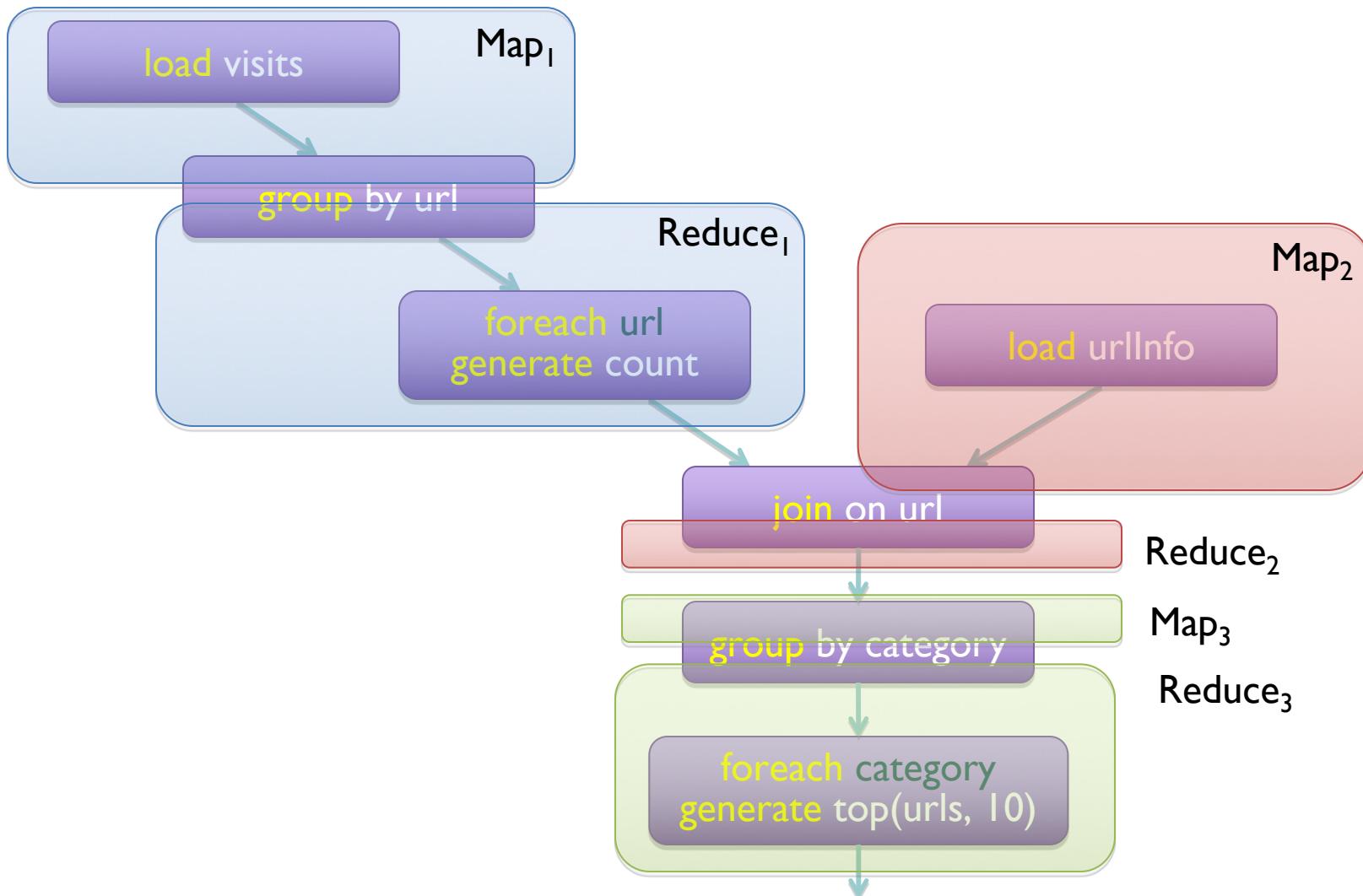
Pig: Example Script

```
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



```

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';
```

Or this?

```

import java.io.IOException;
import java.util.ArrayList;
import java.util.Iterator;
import java.util.List;

import org.apache.hadoop.fs.Path;
import org.apache.hadoop.io.LongWritable;
import org.apache.hadoop.io.Text;
import org.apache.hadoop.mapreduce.Mapper;
import org.apache.hadoop.mapreduce.Reducer;
import org.apache.hadoop.mapreduce.OutputCollector;
import org.apache.hadoop.mapred.RecordReader;
import org.apache.hadoop.mapred.Reducer;
import org.apache.hadoop.mapred.Reporter;
import org.apache.hadoop.mapred.SequenceFileInputFormat;
import org.apache.hadoop.mapred.SequenceFileOutputFormat;
import org.apache.hadoop.mapred.TextInputFormat;
import org.apache.hadoop.mapred.jobcontrol.Job;
import org.apache.hadoop.mapred.jobcontrol.JobC ontrol;
import org.apache.hadoop.mapred.lib.IdentityMapper;

public class MRExample {
    public static class LoadPages extends MapReduceBase
        implements Mapper<LongWritable, Text, Text, Text> {
    }

    public void map(LongWritable k, Text val,
                   OutputCollector<Text, Text> oc,
                   Reporter reporter) throws IOException {
        // Pull the key out
        String line = val.toString();
        int firstComma = line.indexOf(',');
        String key = line.substring(0, firstComma);
        String value = line.substring(firstComma + 1);
        Text outKey = new Text(key);
        // Prepend an index to the value so we know which file
        // it came from.
        Text outVal = new Text("1" + value);
        oc.collect(outKey, outVal);
    }
}

public static class LoadAndFilterUsers extends MapReduceBase
    implements Mapper<LongWritable, Text, Text, Text> {
}

public void map(LongWritable k, Text val,
                OutputCollector<Text, Text> oc,
                Reporter reporter) throws IOException {
    // Pull the key out
    String line = val.toString();
    int firstComma = line.indexOf(',');
    String value = line.substring(firstComma + 1);
    int age = Integer.parseInt(value);
    if (age < 18 || age > 25) return;
    String key = line.substring(0, firstComma);
    Text outKey = new Text(key);
    // Prepend an index to the value so we
    // know which file
    Text outVal = new Text("2" + value);
    oc.collect(outKey, outVal);
}

public static class Join extends MapReduceBase
    implements Reducer<Text, Text, Text, Text> {
}

public void reduce(Text key,
                  Iterator<Text> iter,
                  OutputCollector<Text, Text> oc,
                  Reporter reporter) throws IOException {
    // For each value, figure out which file it's from and
    // Only output the first 100 records
    reporter.setStatus("OK");
}

// Do the cross product and collect the values
for (String s1 : first) {
    for (String s2 : second) {
        String outval = key + "," + s1 + "," + s2;
        oc.collect(null, new Text(outval));
        reporter.setStatus("OK");
    }
}
}

public static class LoadJoined extends MapReduceBase
    implements Mapper<Text, Text, LongWritable> {
    public void map(
        Text k,
        Text val,
        OutputColle ctor<Text, LongWritable> oc,
        Reporter reporter) throws IOException {
        // Find the user
        String line = val.toString();
        int firstComma = line.indexOf(',');
        int secondComma = line.indexOf(',', firstComma + 1);
        String key = line.substring(firstComma, secondComma);
        // drop the rest of the record, I don't need it anymore.
        // just pass a 1 for the combiner/reducer to sum instead.
        Text outkey = new Text(key);
        oc.collect(outkey, new LongWritable(1L));
    }
}

public static class ReduceUrls extends MapReduceBase
    implements Reducer<Text, LongWritable, WritableComparable,
    Writable> {
    public void reduce(
        Text key,
        Iterator<LongWritable> iter,
        OutputCollector<WritableComparable, Writable> oc,
        Reporter reporter) throws IOException {
        // Add up all the values we see
        long sum = 0;
        while (iter.hasNext()) {
            sum += iter.next().get();
        }
        reporter.setStatus("OK");
    }
    oc.collect(key, new LongWritable(sum));
}

public static class LoadClicks extends MapReduceBase
    implements Mapper<WritableComparable, Writable, LongWritable,
    Text> {
    public void map(
        WritableComparable key,
        Writable val,
        OutputCollector<LongWritable, Text> oc,
        Reporter reporter) throws IOException {
        oc.collect((LongWritable)val, (Text)key);
    }
}

public static class LimitClicks extends MapReduceBase
    implements Reducer<LongWritable, Text, LongWritable, Text> {
    int count = 0;
    public void reduce(
        LongWritable key,
        Iterator<Text> iter,
        OutputCollector<LongWritable, Text> oc,
        Reporter reporter) throws IOException {
        // Only output the first 100 records
        reporter.setStatus("OK");
    }
}

lp.setOutputKeyClass(Text.class);
lp.setOutputValueClass(Text.class);
lp.setMapperClass(LoadPages.class);
FileInputFormat.addInputPath(lp, new Path("/user/gates/pages"));
FileOutputFormat.setOutputPath(lp,
    new Path("/user/gates/tmp/indexed_pages"));
lp.setNumReduceTasks(0);
Job loadPages = new Job(lp);

JobConf lfu = new JobConf(MRExample.class);
lfu.setJobName("Load and Filter Users");
lfu.setInputFormat(TextInputFormat.class);
lfu.setOutputKeyClass(Text.class);
lfu.setOutputValueClass(Text.class);
lfu.setMapperClass(LoadAndFilterUsers.class);
FileInputFormat.addInputPath(lfu, new Path("/user/gates/users"));
FileOutputFormat.setOutputPath(lfu,
    new Path("/user/gates/tmp/filtered_users"));
lfu.setNumReduceTasks(0);
Job loadUsers = new Job(lfu);

JobConf join = new JobConf();
join.setJobName("Join Users and Pages");
join.setInputFormat(KeyValueTextInputFormat.class);
join.setOutputKeyClass(Text.class);
join.setOutputValueClass(Text.class);
join.setMapperClass(JoinMapper.class);
join.setCombinerClass(JoinCombiner.class);
join.setReducerClass(JoinReducer.class);
FileInputFormat.addInputPath(join, new Path("/user/gates/tmp/indexed_pages"));
FileInputFormat.addInputPath(join, new Path("/user/gates/tmp/filtered_users"));
FileOutputFormat.setOutputPath(join, new Path("/user/gates/tmp/join"));
join.setNumReduceTasks(50);
Job joinJob = new Job(join);
joinJob.addDependingJob(loadPages);
joinJob.addDependingJob(loadUsers);
joinJob.setMapperClass(LoadJoined.class);
group.setMapperClass(ReduceUrls.class);
group.setCombinerClass(ReduceUrls.class);
group.setReducerClass(group);
FileInputFormat.addInputPath(group, new Path("/user/gates/tmp/joined"));
FileOutputFormat.setOutputPath(group, new Path("/user/gates/tmp/grouped"));
group.setNumReduceTasks(50);
Job groupJob = new Job(group);
groupJob.addDependingJob(joinJob);

JobConf top100 = new JobConf(MRE xample.class);
top100.setJobName("Top 100 sites");
top100.setInputFormat(SequenceFileInputFormat.class);
top100.setOutputKeyClass(LongWritable.class);
top100.setOutputValueClass(Text.class);
top100.setMapperClass(SequenceFileInputFormat.class);
top100.setCombinerClass(LimitClicks.class);
top100.setReducerClass(LimitClicks.class);
FileInputFormat.addInputPath(top100, new Path("/user/gates/tmp/grouped"));
FileOutputFormat.setOutputPath(top100, new Path("/user/gates/tmp/100sites"));
top100.setNumReduceTasks(1);
Job limitJob = new Job(top100);
limitJob.addDependingJob(groupJob);

```

But isn't Pig slower?

Sure, but c can be slower than assembly too...



Pig: Basics

Sequence of statements manipulating relations (aliases)

Data model

atoms

tuples

bags

maps

json

Pig: Common Operations

LOAD: load data (from HDFS)

FOREACH ... GENERATE: per tuple processing

FILTER: discard unwanted tuples “**map**”

“*reduce*” GROUP/COGROUP: group tuples
JOIN: relational join

STORE: store data (to HDFS)

Pig: GROUPing

```
A = LOAD 'myfile.txt' AS (f1: int, f2: int, f3: int);
```

```
(1, 2, 3)  
(4, 2, 1)  
(8, 3, 4)  
(4, 3, 3)  
(7, 2, 5)  
(8, 4, 3)
```

```
X = GROUP A BY f1;
```

```
(1, {(1, 2, 3)})  
(4, {(4, 2, 1), (4, 3, 3)})  
(7, {(7, 2, 5)})  
(8, {(8, 3, 4), (8, 4, 3)})
```

Pig: COGROUPing

A:

(1, 2, 3)
(4, 2, 1)
(8, 3, 4)
(4, 3, 3)
(7, 2, 5)
(8, 4, 3)

B:

(2, 4)
(8, 9)
(1, 3)
(2, 7)
(2, 9)
(4, 6)
(4, 9)

```
X = COGROUP A BY $0, B BY $0;
```

```
(1, {(1, 2, 3)}, {(1, 3)})  
(2, {}, {(2, 4), (2, 7), (2, 9)})  
(4, {(4, 2, 1), (4, 3, 3)}, {(4, 6), (4, 9)})  
(7, {(7, 2, 5)}, {})  
(8, {(8, 3, 4), (8, 4, 3)}, {(8, 9)})
```

Pig: JOINing

A:

(1, 2, 3)
(4, 2, 1)
(8, 3, 4)
(4, 3, 3)
(7, 2, 5)
(8, 4, 3)

B:

(2, 4)
(8, 9)
(1, 3)
(2, 7)
(2, 9)
(4, 6)
(4, 9)

```
X = JOIN A BY $0, B BY $0;
```

(1,2,3,1,3)
(4,2,1,4,6)
(4,3,3,4,6)
(4,2,1,4,9)
(4,3,3,4,9)
(8,3,4,8,9)
(8,4,3,8,9)

Pig UDFs

User-defined functions:

Java

Python

JavaScript

Ruby

...

UDFs make Pig arbitrarily extensible

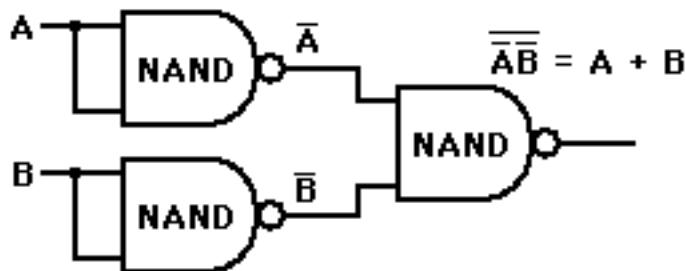
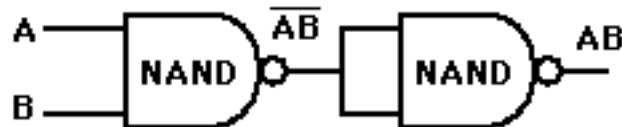
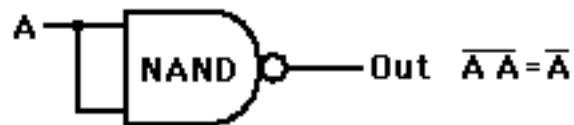
Express “core” computations in UDFs

Take advantage of Pig as glue code for scale-out plumbing

An aerial photograph of a large data center complex during sunset. The sky is a warm orange and yellow. In the foreground, there's a mix of green fields and industrial buildings, including several large white data center pods arranged in rows. A highway runs through the middle ground. The overall scene is a blend of rural and industrial landscapes.

The datacenter *is* the computer!
What's the instruction set?
Okay, let's fix this!

Analogy: NAND Gates are universal



Let's design a data processing
language "from scratch"!

What ops do you need?

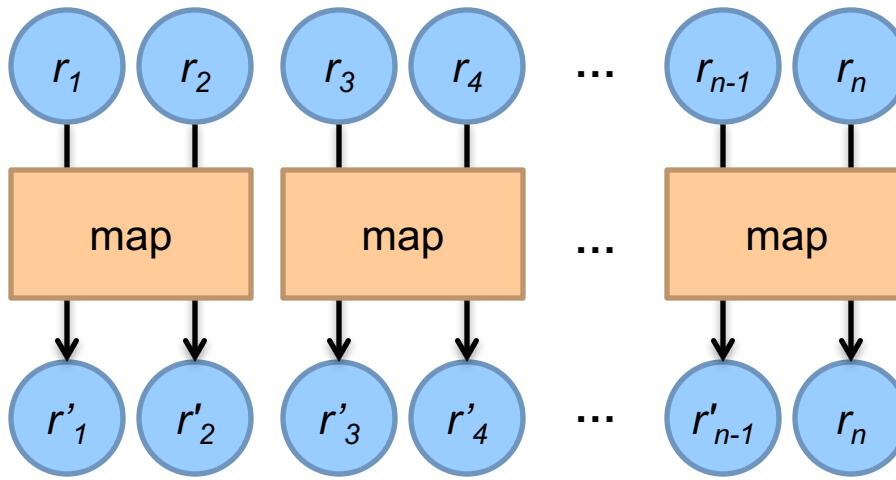
(Why is MapReduce the way it is?)

Data-Parallel Dataflow Languages

We have a collection of **records**,
want to apply a bunch of operations
to compute some result

Assumption: static collection of records
(what's the limitation here?)

We need per-record processing



Remarks: Easy to parallelize maps,
record to “mapper” assignment is an implementation detail

Map alone isn't enough

(If we want more than embarrassingly parallel processing)

Where do intermediate results go?

We need an addressing mechanism!

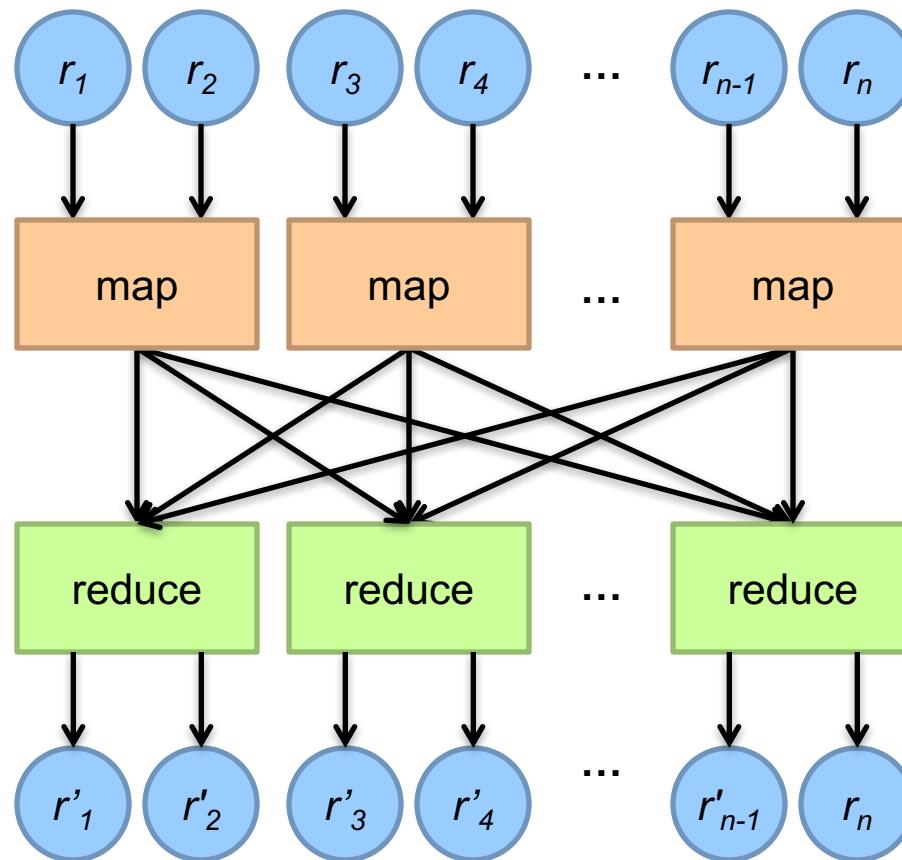
What's the semantics of the group by?

Once we resolve the addressing, apply another computation

That's what we call reduce!

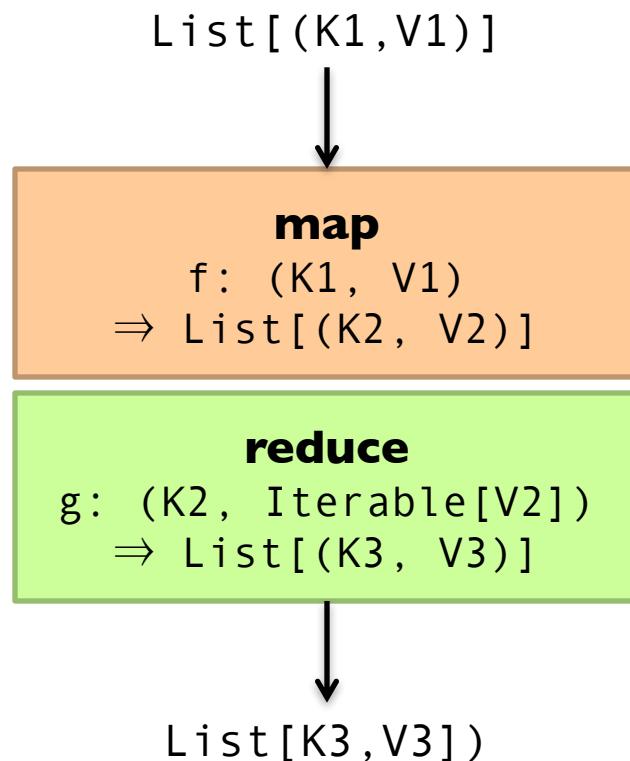
(What's with the sorting then?)

MapReduce



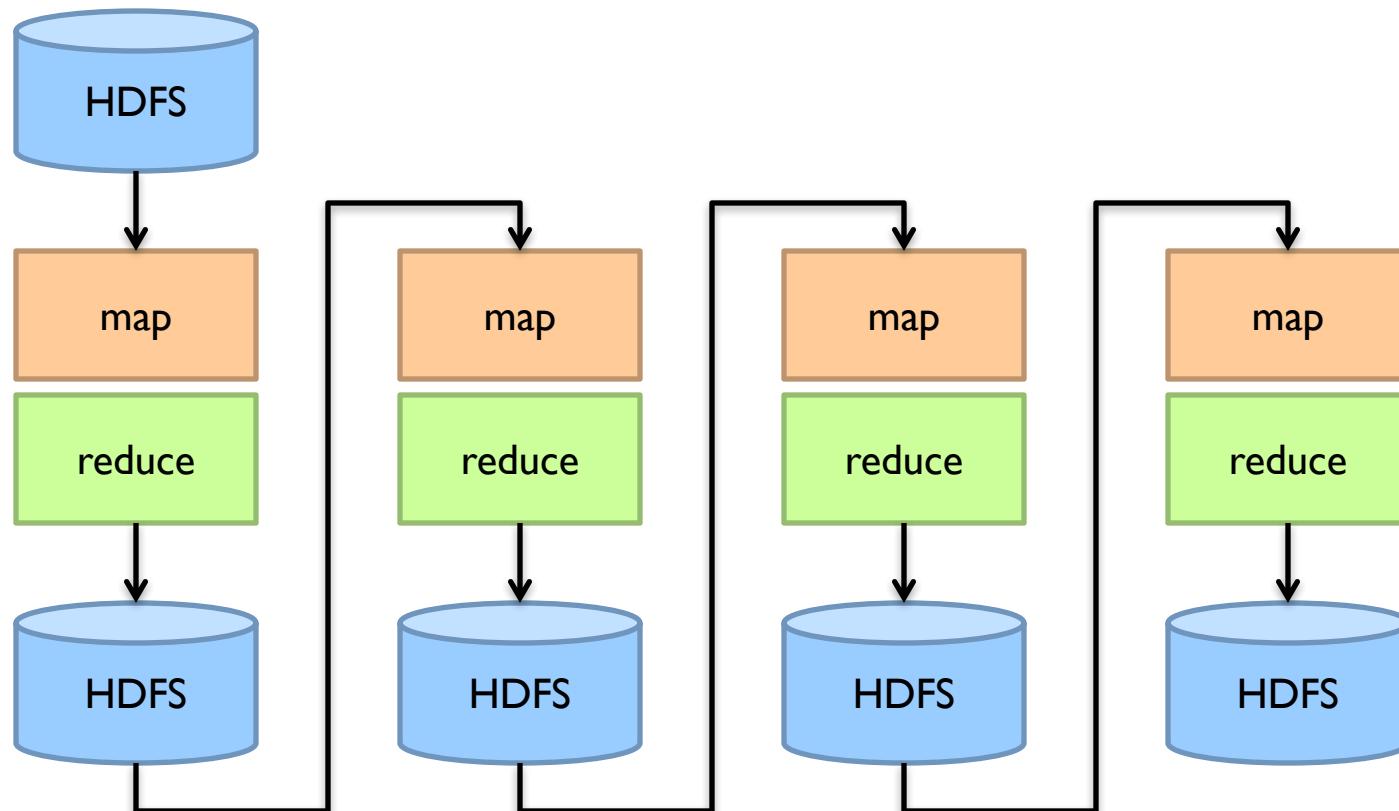
MapReduce is the minimally “interesting” dataflow!

MapReduce



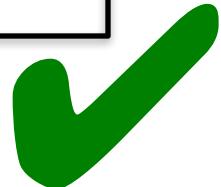
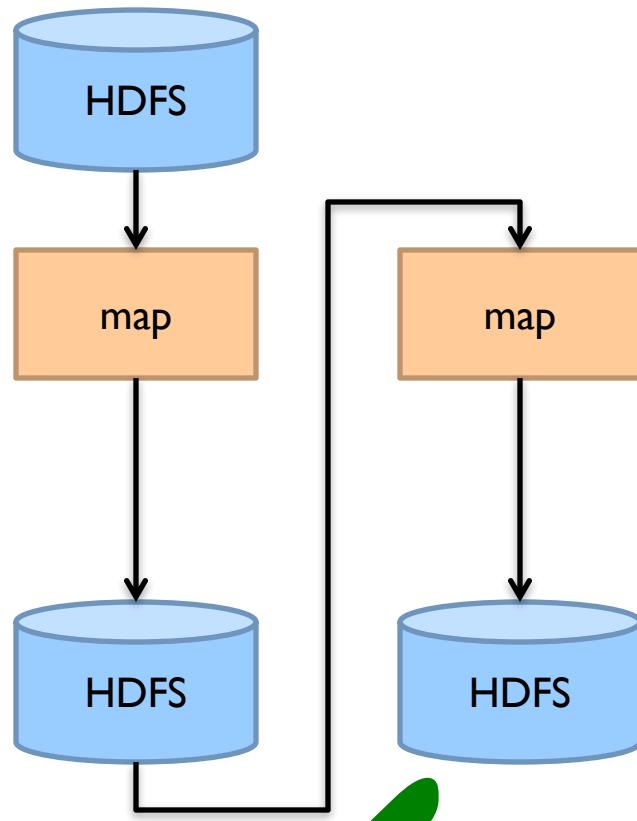
(note we're abstracting the “data-parallel” part)

MapReduce Workflows

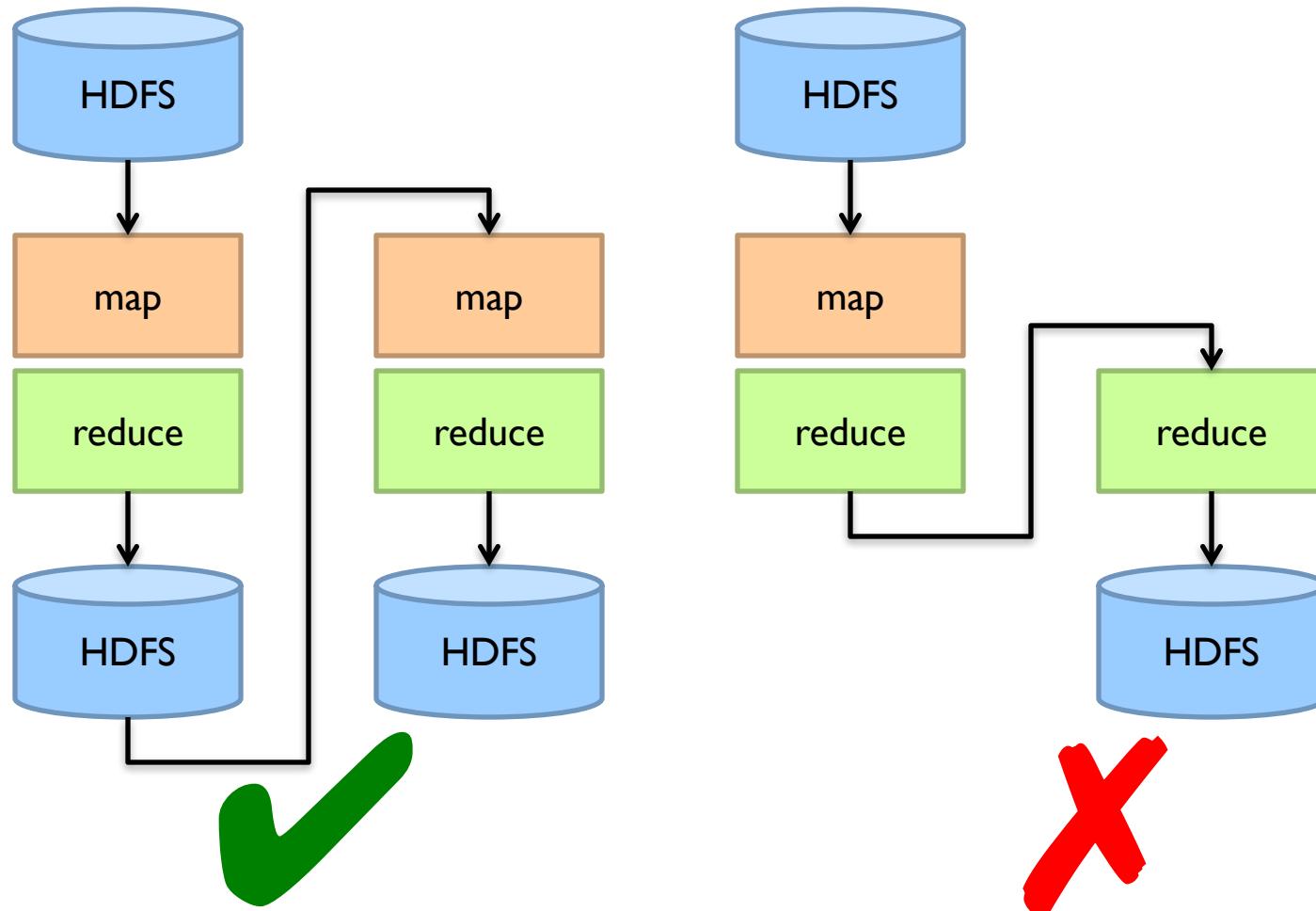


What's wrong?

Want MM?



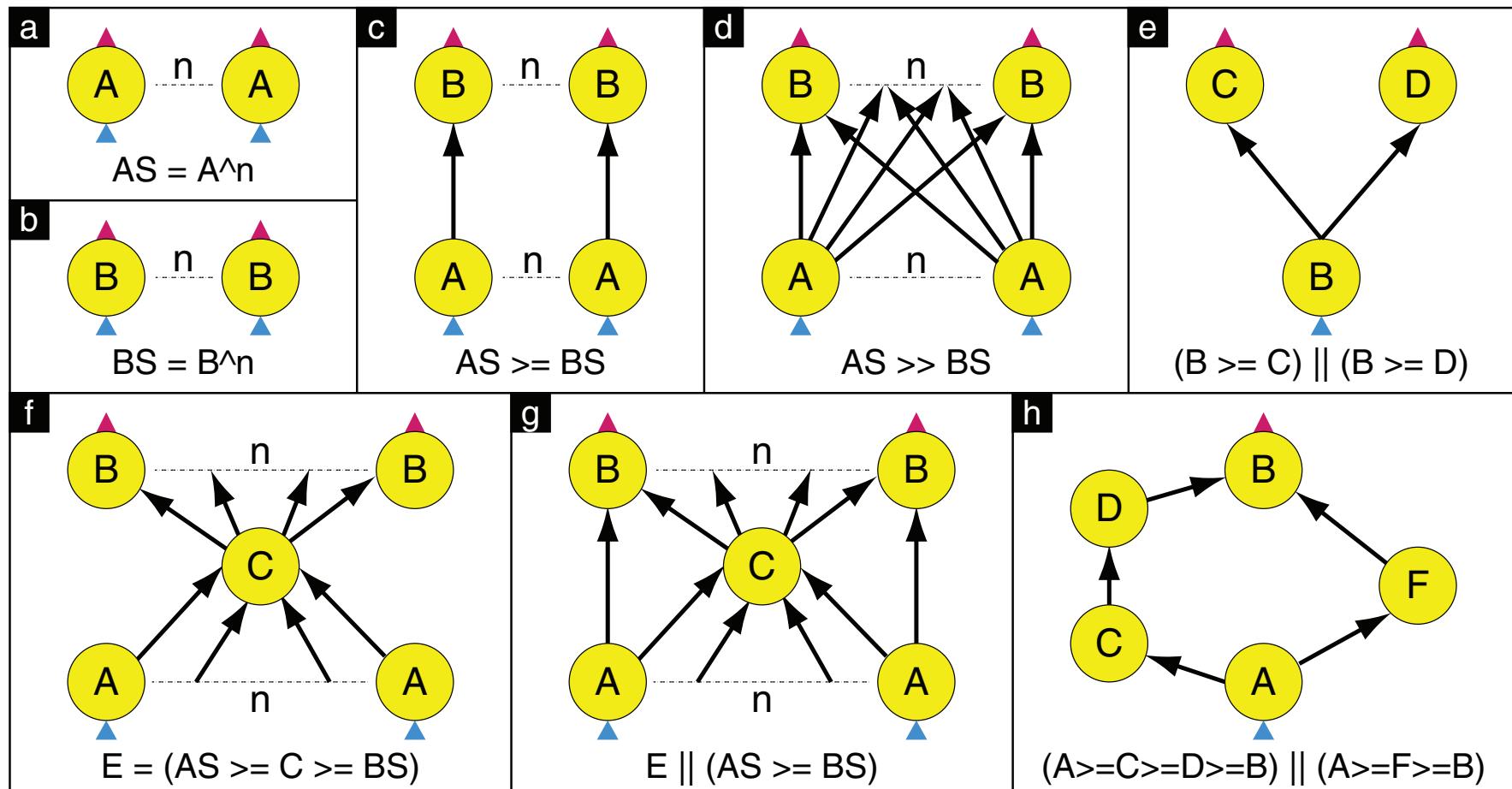
Want MRR?



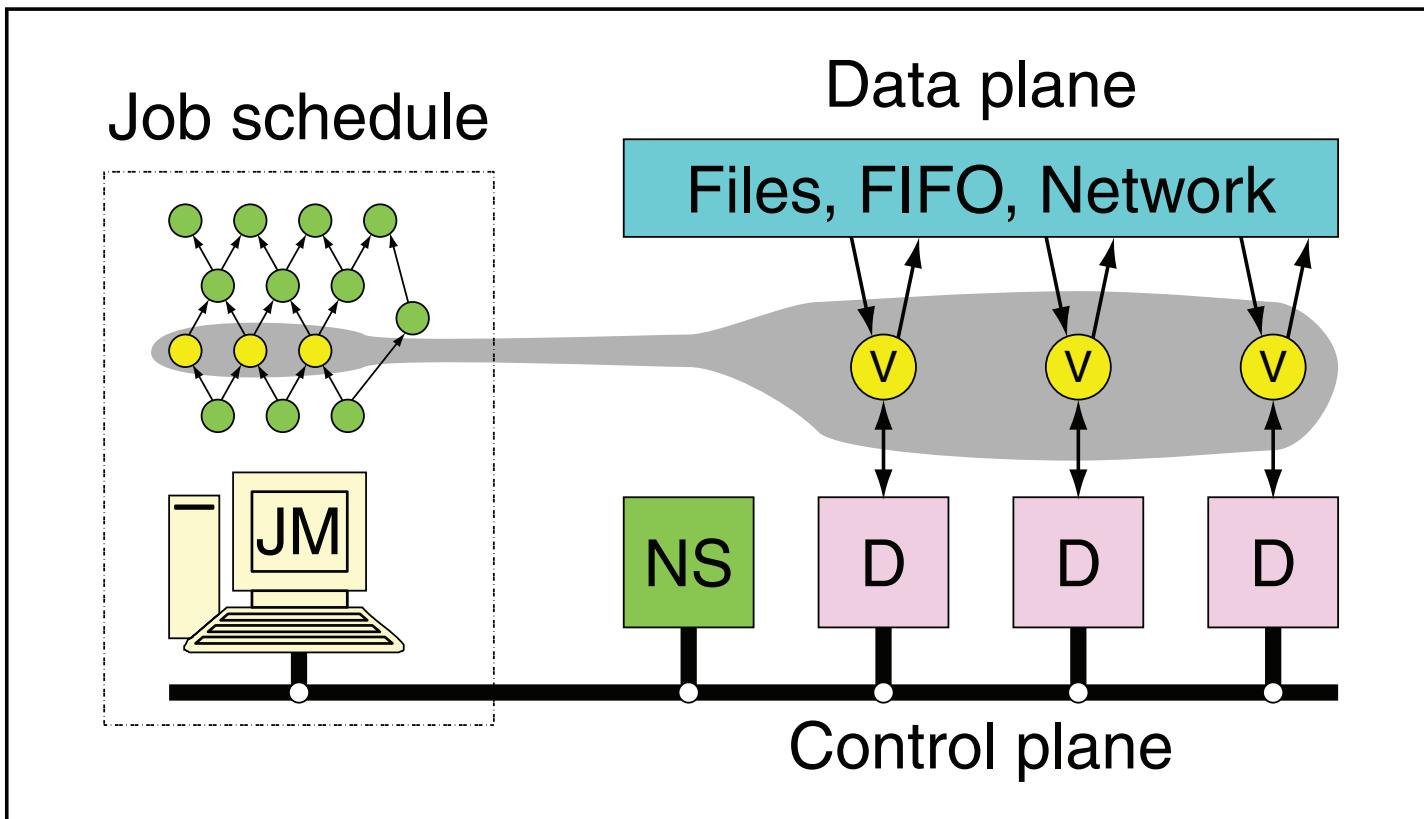
An aerial photograph of a large data center complex during sunset. The sky is a warm orange and yellow. In the foreground, there are several large white industrial buildings, some with flat roofs and others with gabled roofs. A parking lot with many cars is visible in front of one of the buildings. To the right, there is a large building with a green roof and a parking lot. In the background, there are more buildings and a highway with traffic. The surrounding land is mostly green fields and pastures.

The datacenter *is* the computer!
Let's enrich the instruction set!

Dryad: Graph Operators



Dryad: Architecture



The Dryad system organization. The job manager (JM) consults the name server (NS) to discover the list of available computers. It maintains the job graph and schedules running vertices (V) as computers become available using the daemon (D) as a proxy. Vertices exchange data through files, TCP pipes, or shared-memory channels. The shaded bar indicates the vertices in the job that are currently running.

Dryad: Cool Tricks

Channel: abstraction for vertex-to-vertex communication

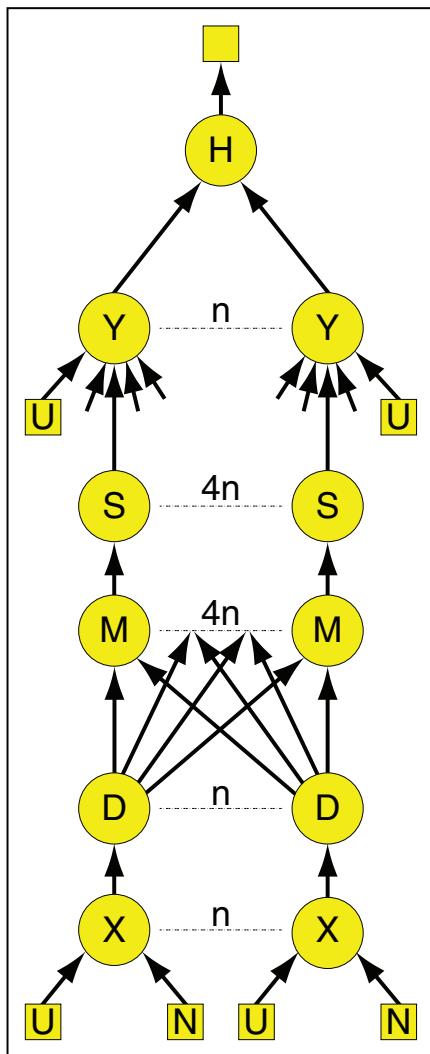
- File
- TCP pipe
- Shared memory

Runtime graph refinement

Size of input is not known until runtime

Automatically rewrite graph based on invariant properties

Dryad: Sample Program



```
GraphBuilder XSet = moduleX^N;
GraphBuilder DSet = moduleD^N;
GraphBuilder MSet = moduleM^(N*4);
GraphBuilder SSet = moduleS^(N*4);
GraphBuilder YSet = moduleY^N;
GraphBuilder HSet = moduleH^1;

GraphBuilder XInputs = (ugriz1 >= XSet) || (neighbor >= XSet);
GraphBuilder YInputs = ugriz2 >= YSet;

GraphBuilder XToY = XSet >= DSet >> MSet >= SSet;
for (i = 0; i < N*4; ++i)
{
    XToY = XToY || (SSet.GetVertex(i) >= YSet.GetVertex(i/4));
}

GraphBuilder YToH = YSet >= HSet;
GraphBuilder HOutputs = HSet >= output;

GraphBuilder final = XInputs || YInputs || XToY || YToH || HOutputs;
```

DryadLINQ

LINQ = Language INtegrated Query

.NET constructs for combining imperative and declarative programming

Developers write in DryadLINQ

Program compiled into computations that run on Dryad

Sound familiar?

What's the solution?

Design a higher-level language

Write a compiler

DryadLINQ: Word Count

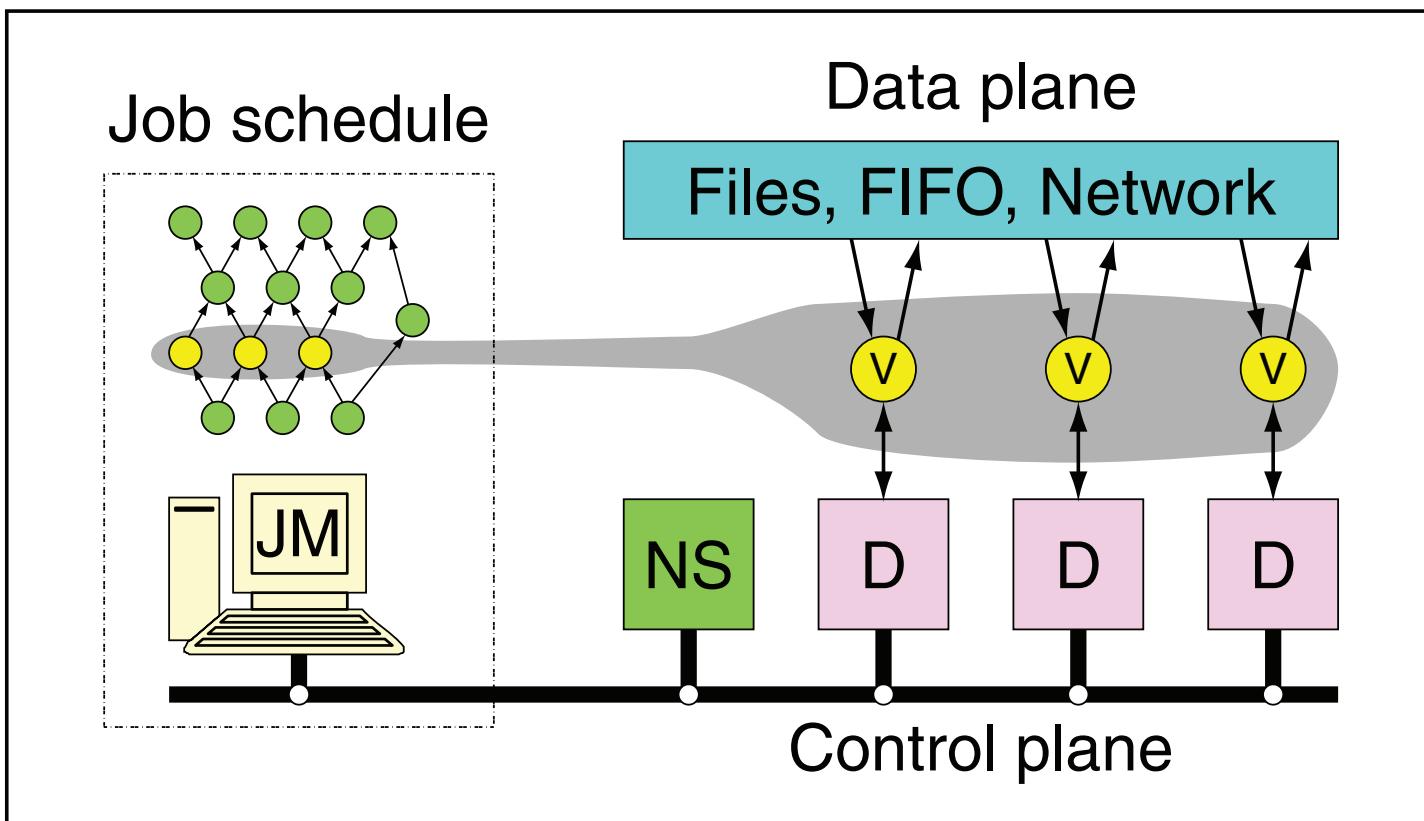
```
PartitionedTable<LineRecord> inputTable =  
    PartitionedTable.Get<LineRecord>(uri);  
  
IQueryable<string> words = inputTable.SelectMany(x => x.line.Split(' '));  
IQueryable<IGrouping<string, string>> groups = words.GroupBy(x => x);  
IQueryable<Pair> counts = groups.Select(x => new Pair(x.Key, x.Count()));  
IQueryable<Pair> ordered = counts.OrderByDescending(x => x.Count());  
IQueryable<Pair> top = ordered.Take(k);
```

Compare:

```
a = load 'file.txt' as (text: chararray);  
b = foreach a generate flatten(TOKENIZE(text)) as term;  
c = group b by term;  
d = foreach c generate group as term, COUNT(b) as count;  
  
store d into 'cnt';
```

Compare and contrast...

What happened to Dryad?



The Dryad system organization. The job manager (JM) consults the name server (NS) to discover the list of available computers. It maintains the job graph and schedules running vertices (V) as computers become available using the daemon (D) as a proxy. Vertices exchange data through files, TCP pipes, or shared-memory channels. The shaded bar indicates the vertices in the job that are currently running.

Data-Parallel Dataflow Languages

We have a collection of **records**,
want to apply a bunch of operations
to compute some result

What are the dataflow operators?

Spark

Answer to “What’s beyond MapReduce?”

Brief history:

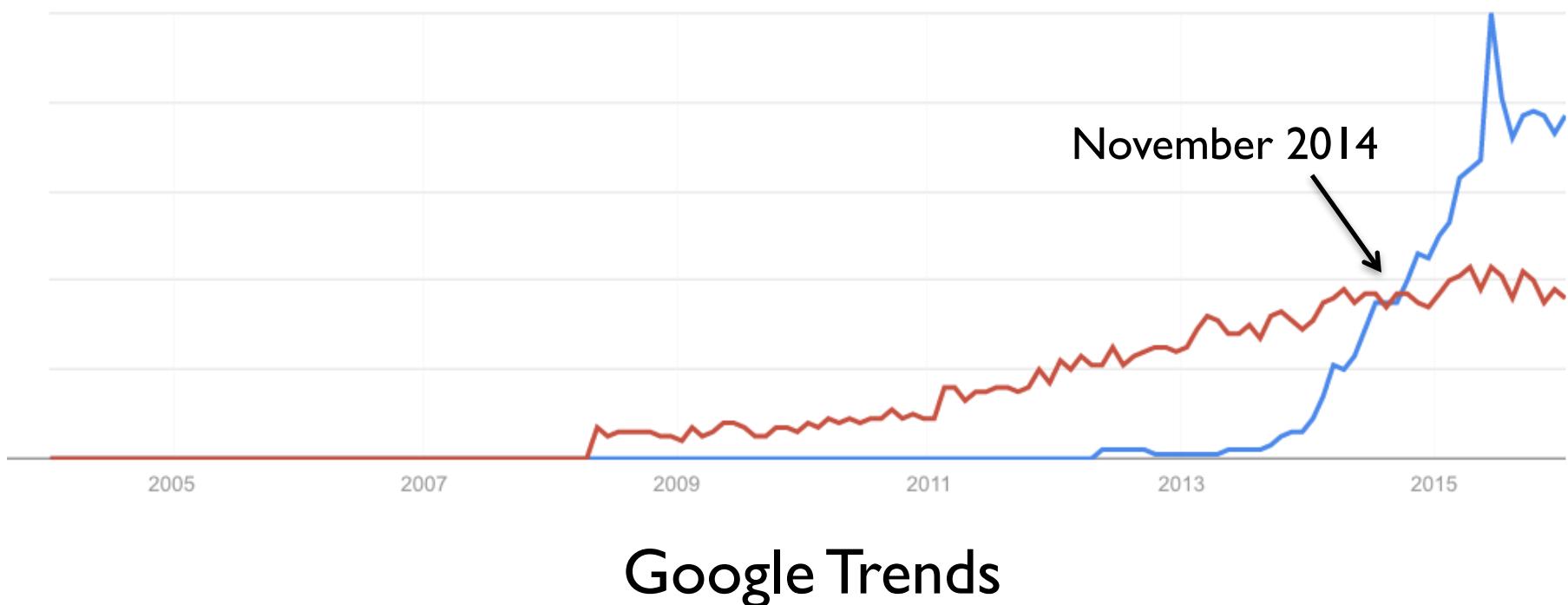
Developed at UC Berkeley AMPLab in 2009

Open-sourced in 2010

Became top-level Apache project in February 2014

Commercial support provided by Databricks

Spark vs. Hadoop

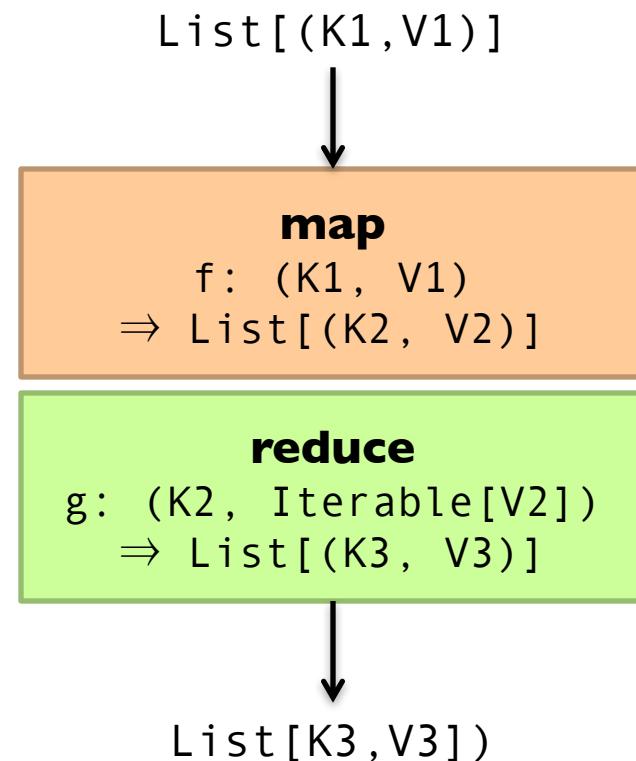


What's an RDD?

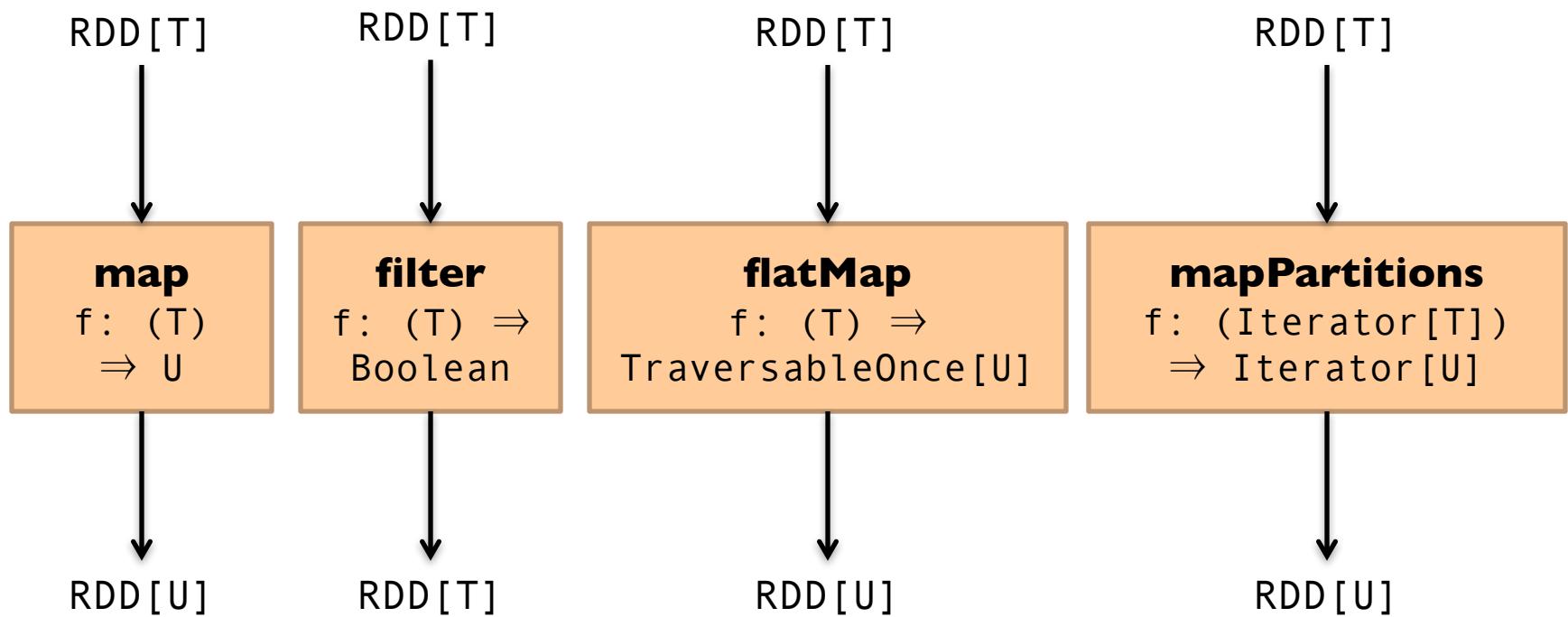
Resilient Distributed Dataset (RDD)

Much more next session...

MapReduce

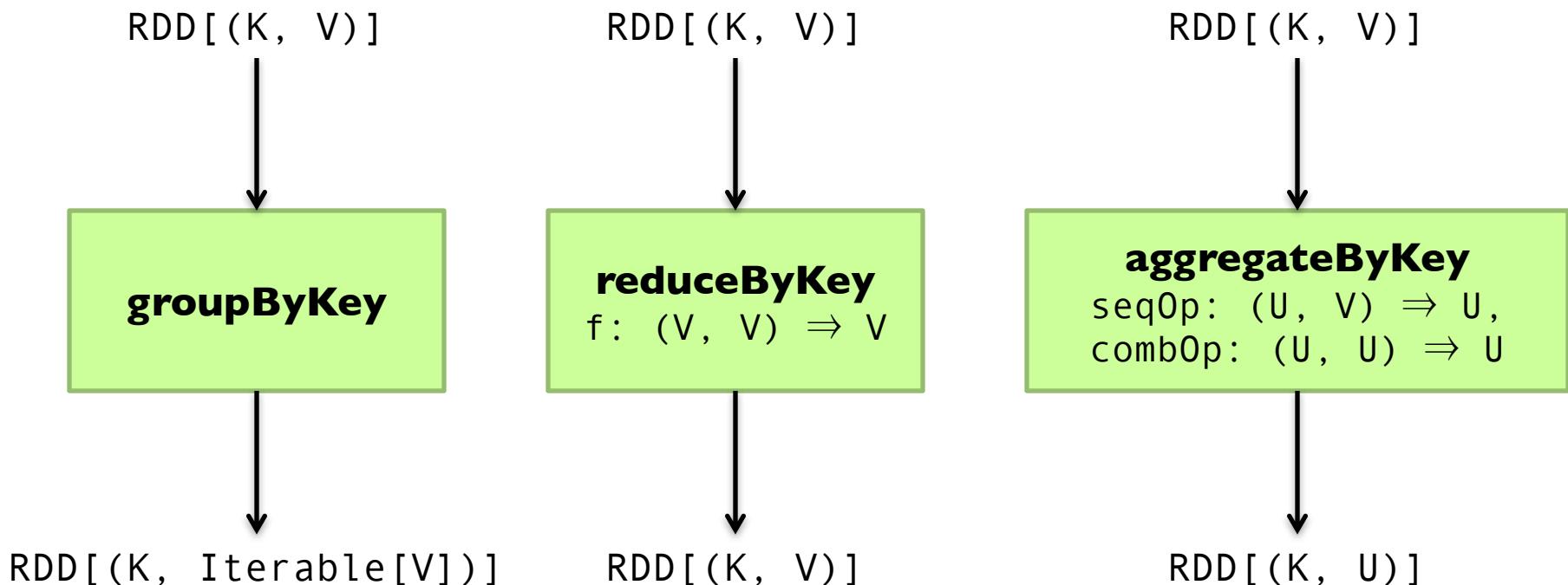


Map-like Operations



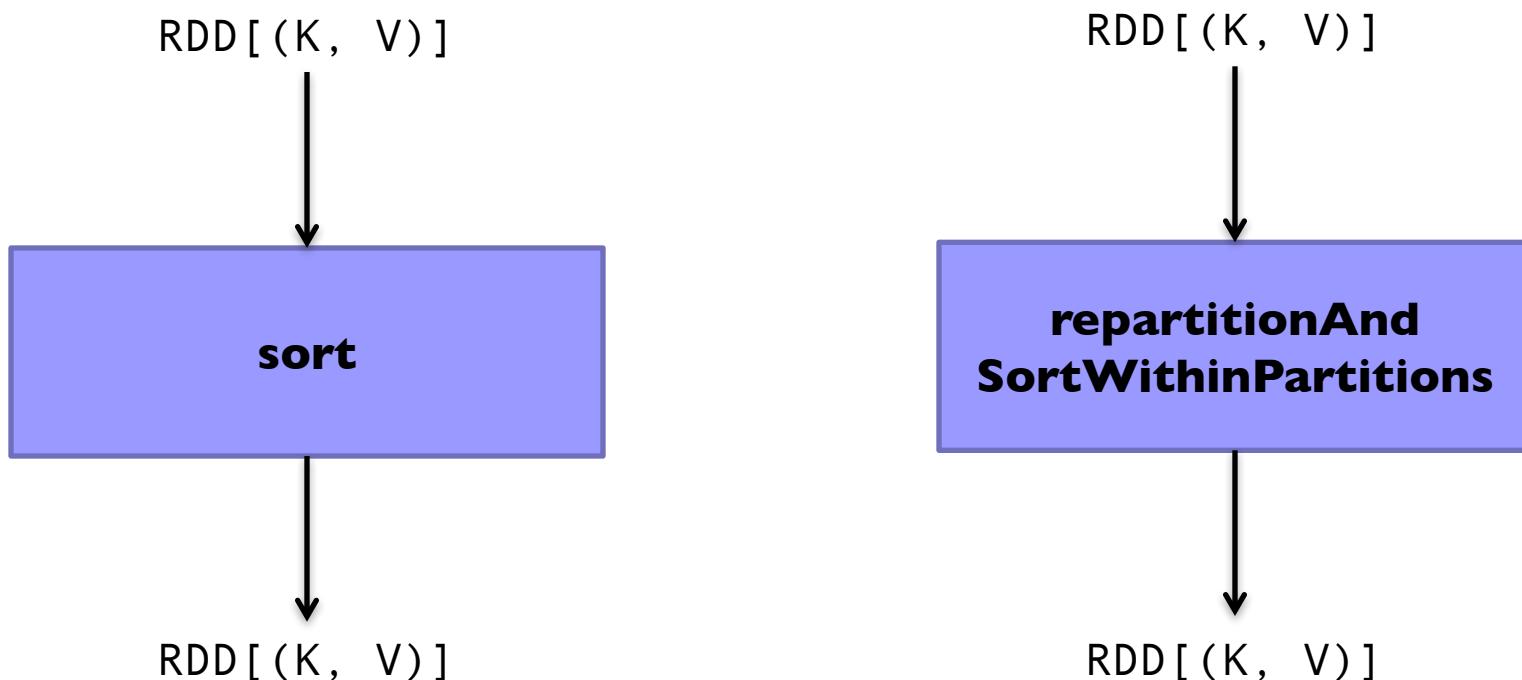
(Not meant to be exhaustive)

Reduce-like Operations



(Not meant to be exhaustive)

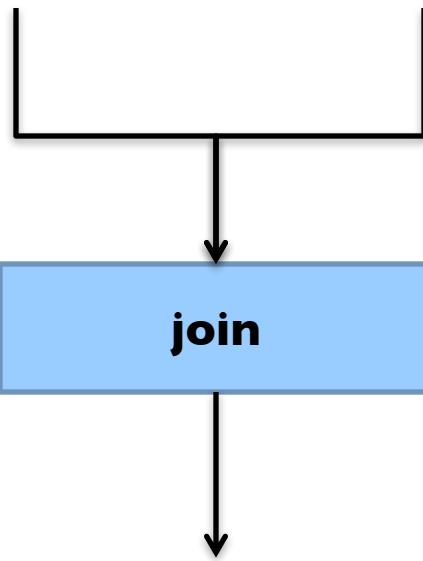
Sort Operations



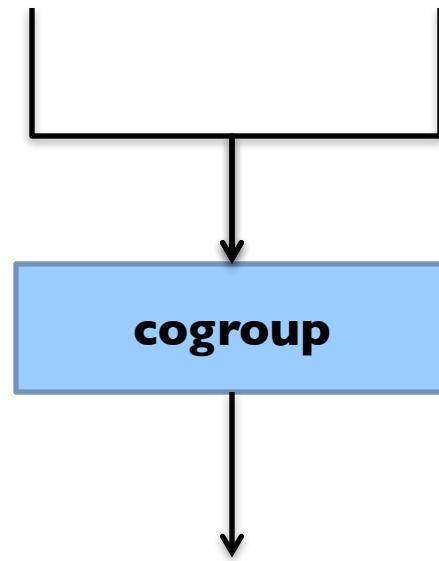
(Not meant to be exhaustive)

Join-like Operations

RDD[(K, V)] RDD[(K, W)]

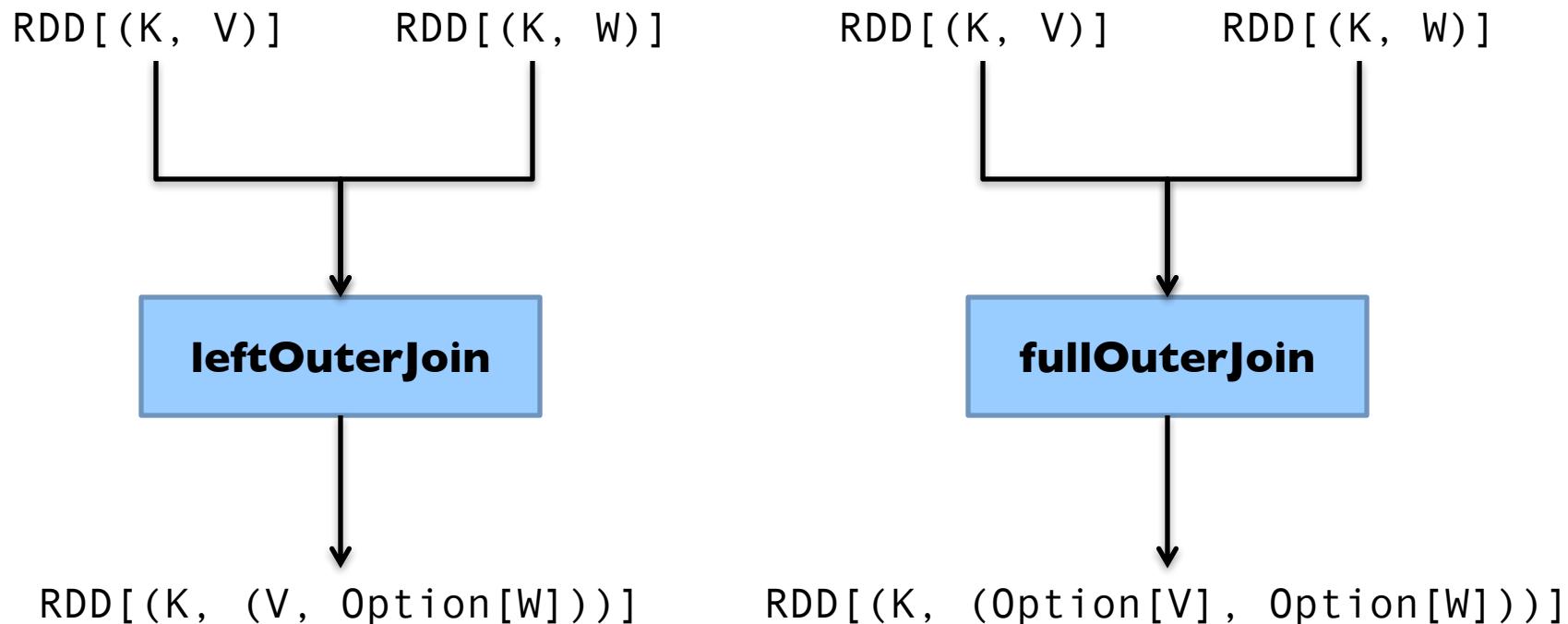


RDD[(K, V)] RDD[(K, W)]



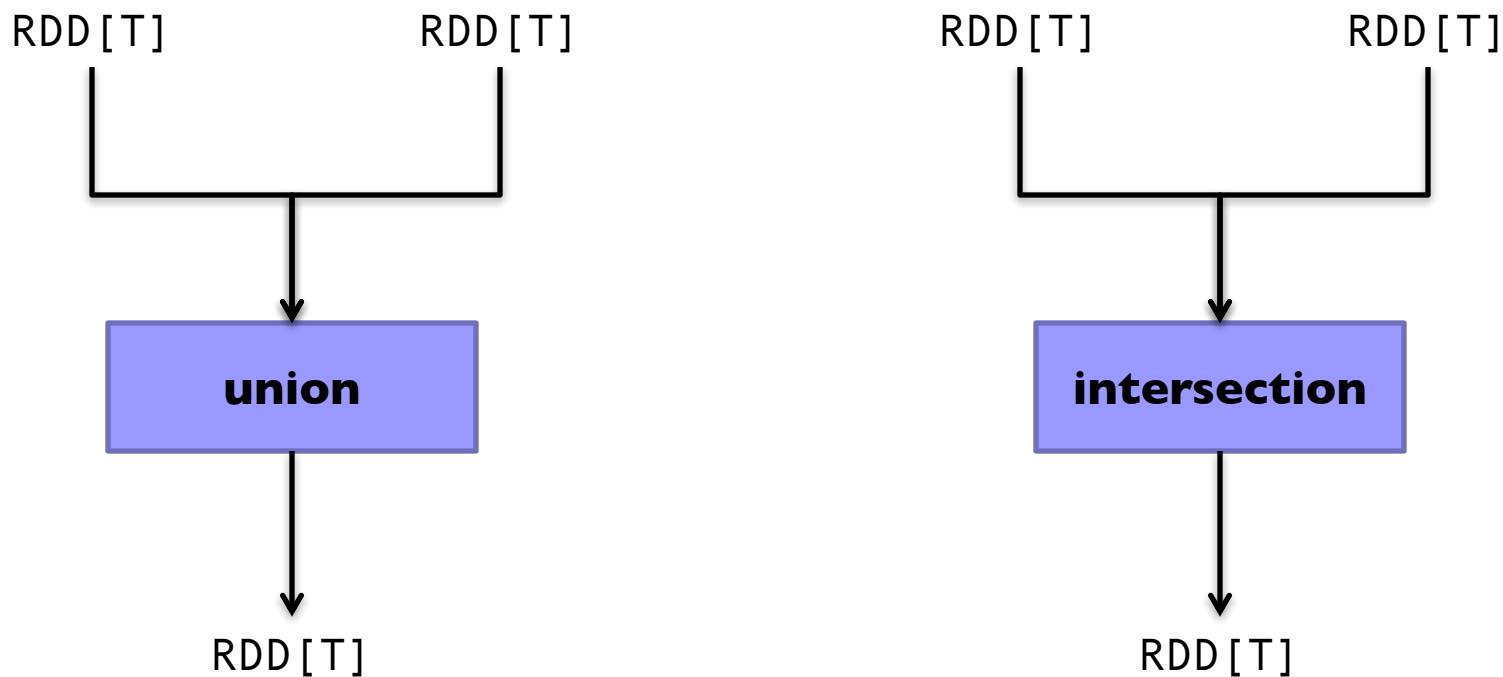
(Not meant to be exhaustive)

Join-like Operations



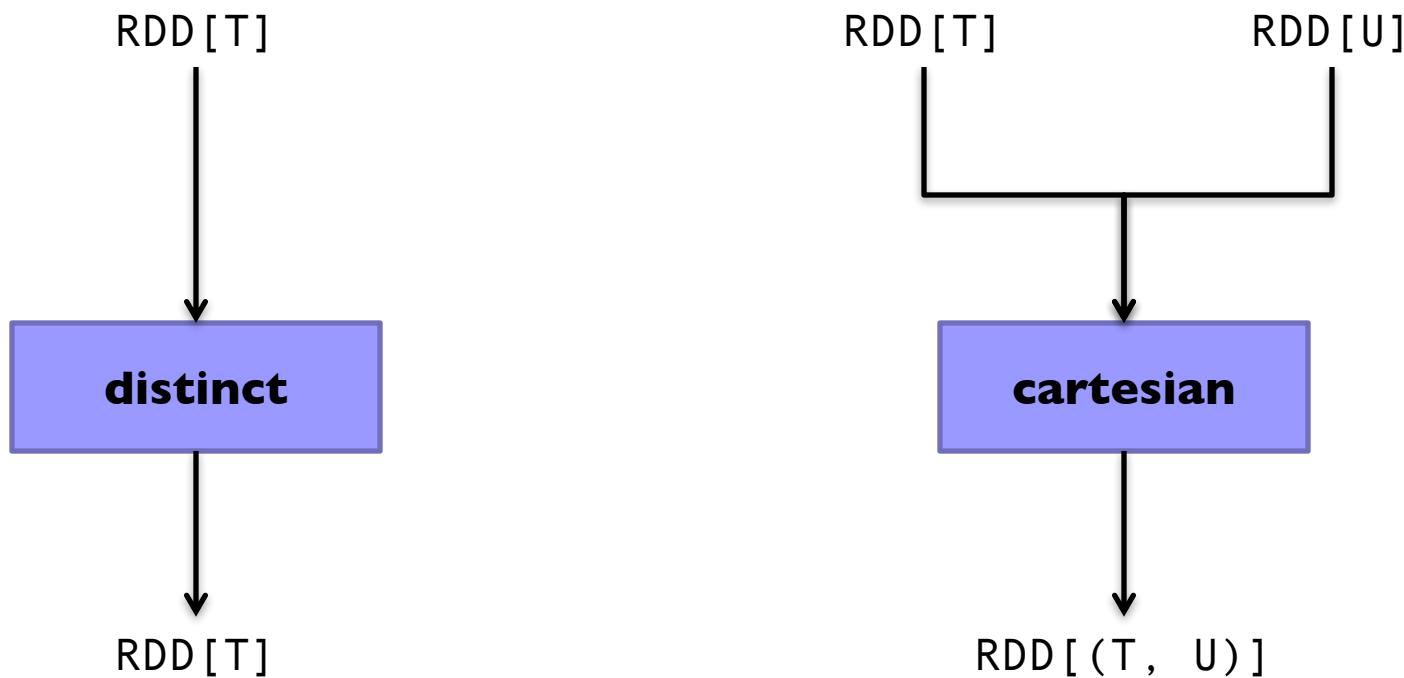
(Not meant to be exhaustive)

Set-ish Operations



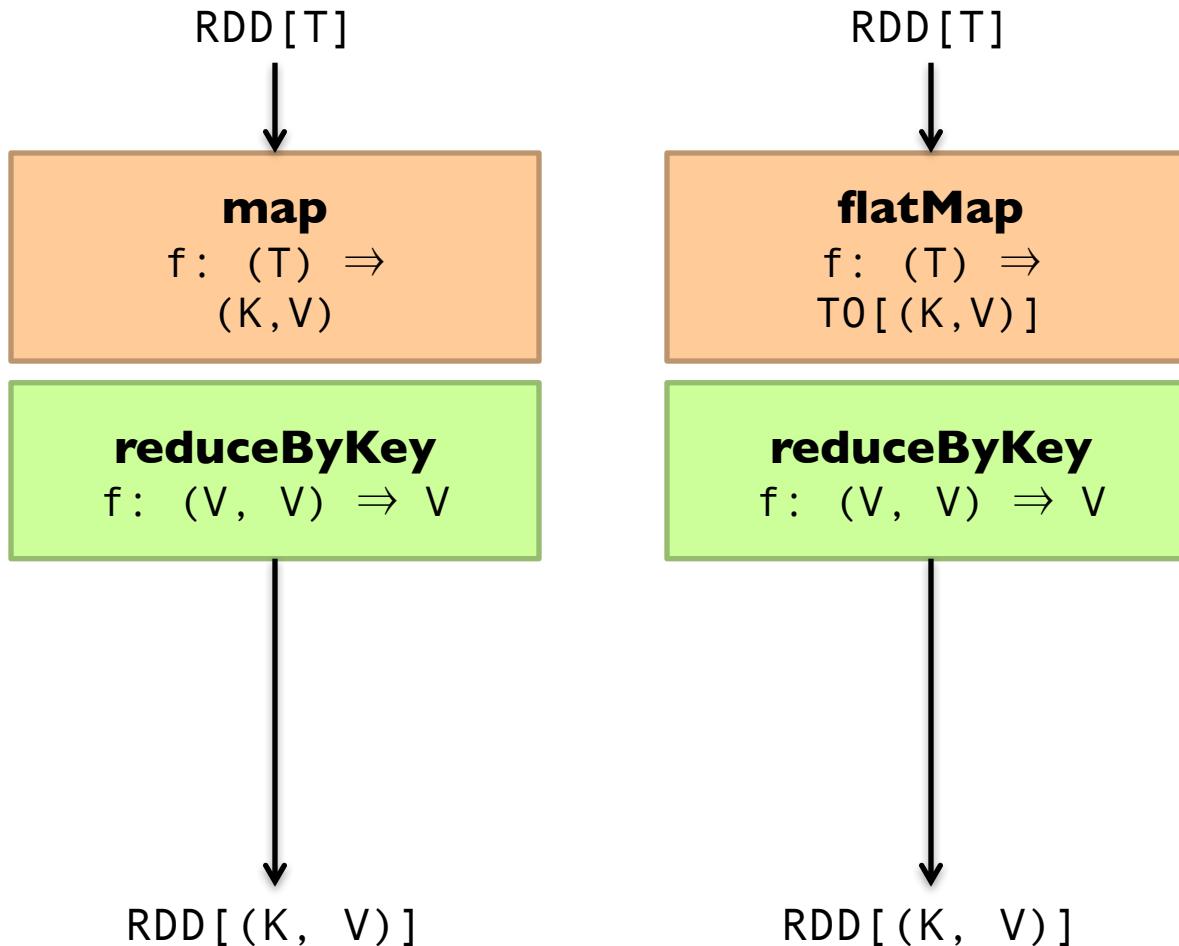
(Not meant to be exhaustive)

Set-ish Operations



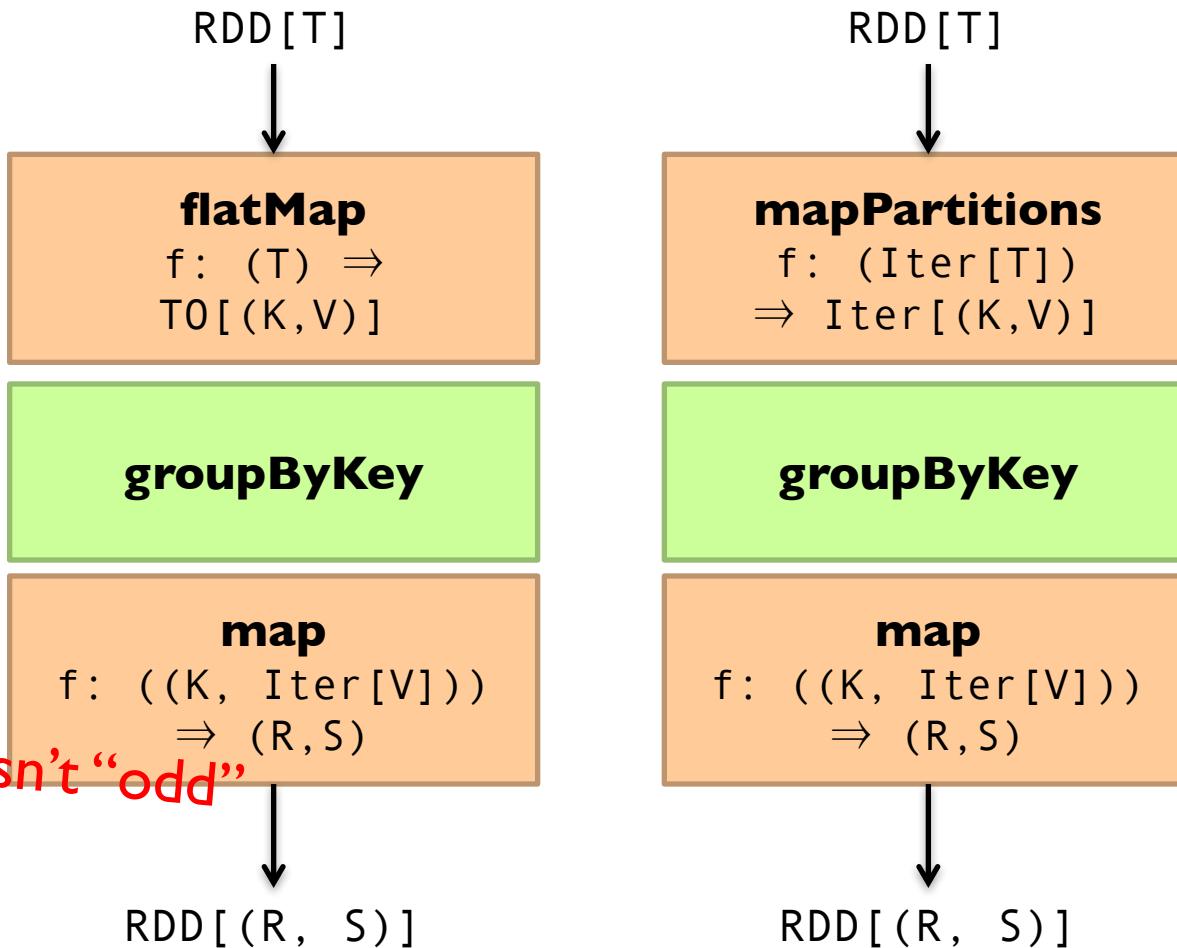
(Not meant to be exhaustive)

MapReduce in Spark?



Not quite...

MapReduce in Spark?



Still not quite...

Spark Word Count

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

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

$$(x, y) \Rightarrow x + y$$

Aside: Scala tuple access notation, e.g., `a._1`

Don't focus on Java verbosity!

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

textFile
  .map(object mapper {
    def map(key: Long, value: Text) =
      tokenize(value).foreach(word => write(word, 1))
  })
  .reduce(object reducer {
    def reduce(key: Text, values: Iterable[Int]) = {
      var sum = 0
      for (value <- values) sum += value
      write(key, sum)
    }
  })
  .saveAsTextFile(args.output())
```

Next Time...

What's an RDD?

How does Spark actually work?

Algorithm design: redux

Meanwhile, at 1600 Amphitheatre Parkway...

Sawzall – circa 2003

Lumberjack – circa ??

Flume(Java) – circa 2009

Cloud Dataflow (Flume + MillWheel) – circa 2014

Flume(Java)

Core data types

`PCollection<T>` - a (possibly huge) immutable bag of elements of type T

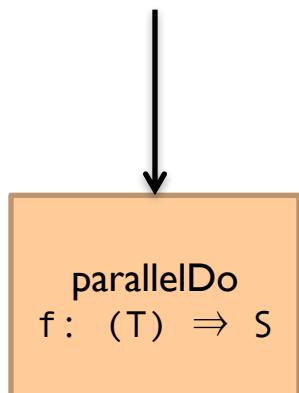
`PTable<K, V>` - a (possibly huge) immutable bag of key-value pairs

Hmm... sounds suspiciously familiar...

Flume(Java)

Primitive operations

PCollection<T>



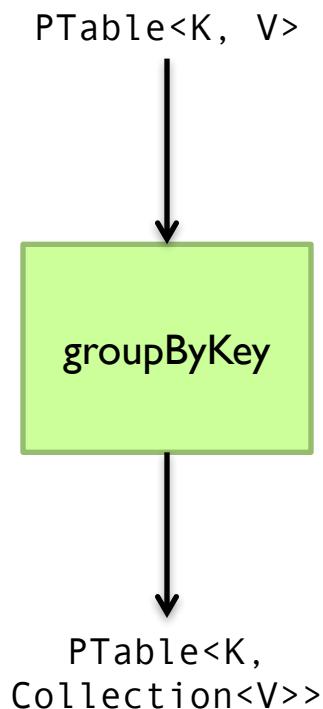
```
PCollection<String> words =  
    lines.parallelDo(new DoFn<String, String>() {  
        void process(String line, EmitFn<String> emitFn) {  
            for (String word : splitIntoWords(line)) {  
                emitFn.emit(word);  
            }  
        }  
    }, collectionOf(strings()));
```

PCollection<S>

Hmm... looks suspiciously familiar...

Flume(Java)

Primitive operations



```
PTable<URL,DocInfo> backlinks =
docInfos.parallelDo(new DoFn<DocInfo, Pair<URL,DocInfo>>() {
    void process(DocInfo docInfo, EmitFn<Pair<URL,DocInfo>> emitFn) {
        for (URL targetUrl : docInfo.getLinks()) {
            emitFn.emit(Pair.of(targetUrl, docInfo));
        }
    }
}, tableOf(recordsOf(URL.class), recordsOf(DocInfo.class))));

PTable<URL,Collections<DocInfo>> referringDocInfos =
backlinks.groupByKey();
```

Hmm... looks suspiciously familiar...

Flume(Java)

Primitive operations

PTable<K,
Collection<V>>



combineValues
 $f: (V, V) \Rightarrow V$



PTable<K, V>

```
PTable<String, Integer> wordsWithOnes =  
    words.parallelDo(  
        new DoFn<String, Pair<String, Integer>>() {  
            void process(String word, EmitFn<Pair<String, Integer>> emitFn) {  
                emitFn.emit(Pair.of(word, 1));  
            }  
        }, tableOf(strings(), ints()));  
  
PTable<String, Collection<Integer>> groupedWordsWithOnes =  
    wordsWithOnes.groupByKey();  
  
PTable<String, Integer> wordCounts =  
    groupedWordsWithOnes.combineValues(  
        new DoFn<Pair<String, Collection<Integer>>, Pair<String, Integer>>() {  
            void process(Pair<String, Collection<Integer>> pair,  
                        EmitFn<Pair<String, Integer>> emitFn) {  
                int sum = 0;  
                for (Integer val: pair.getValue()) {  
                    sum += val;  
                }  
                emitFn.emit(Pair.of(pair.getKey(), sum));  
            }  
        }, tableOf(strings(), ints()));
```

Hmm... looks suspiciously familiar...

Data-Parallel Dataflow Languages

We have a collection of **records**,
want to apply a bunch of operations
to compute some result

Pig, Dryad(LINQ), Flume(Java), Spark
are all variations on a theme!

Assumption: static collection of records
What if this assumption is violated?



Questions?

Remember: Assignment I due Tuesday 2:30pm