UNIVERSITY OF WATERLOO

Data-Intensive Distributed Computing

CS 451/651 431/631 (Winter 2018)

Part 2: From MapReduce to Spark (1/2)

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

Source: Wikipedia (The Scream)

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!

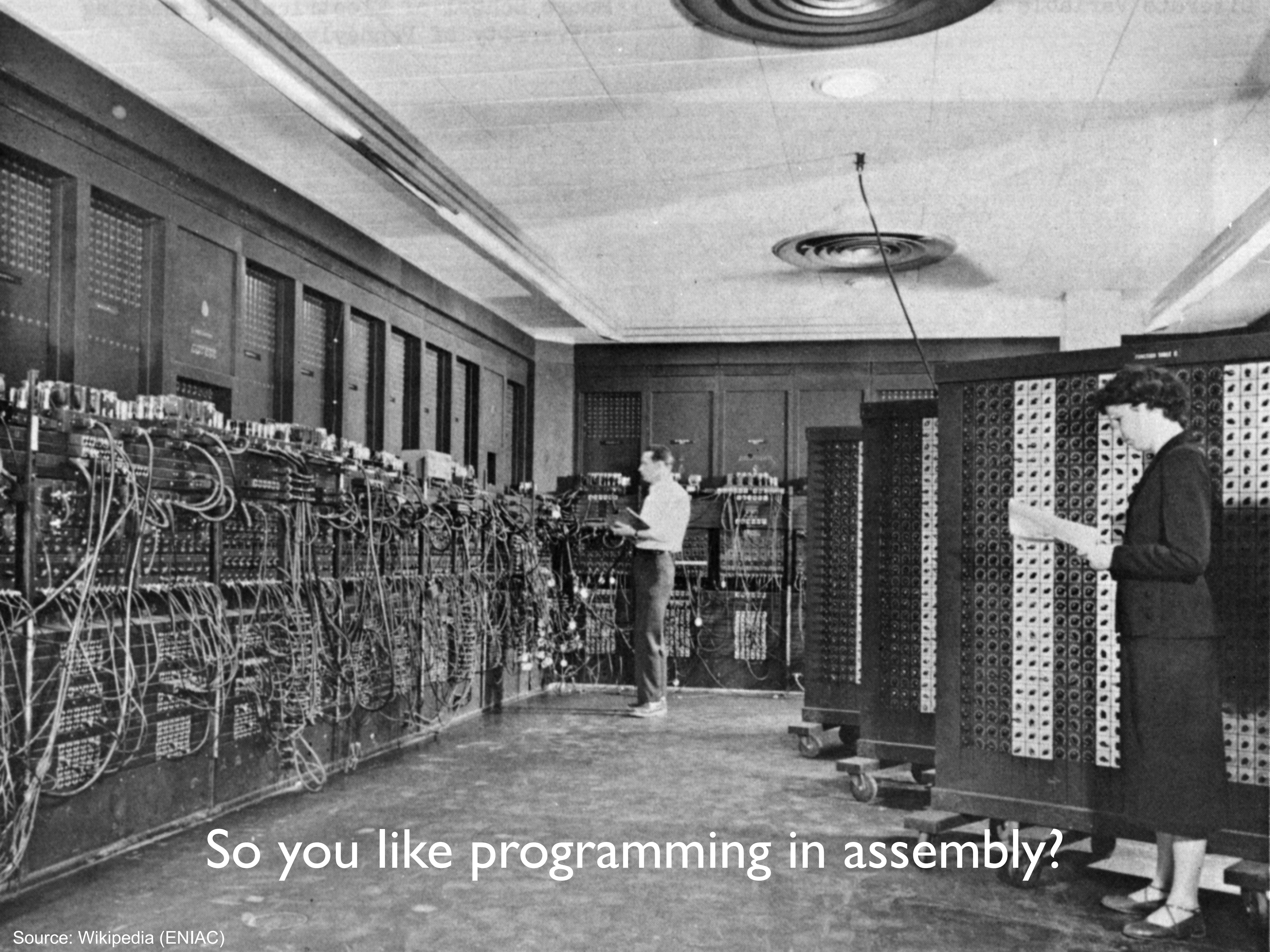
There’s no such thing as “consistent data”

Watch out for corner cases

Isolate unexpected behavior, bring local

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

Source: Google



So you like programming in assembly?

Source: Wikipedia (ENIAC)

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

Source: Wikipedia (DeLorean time machine)

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)

facebook®

What we really need is SQL!

Answer:

YAHOO!®

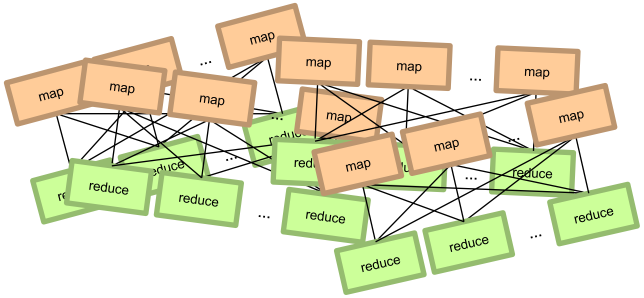
What we really need is a scripting language!

Answer:

facebook

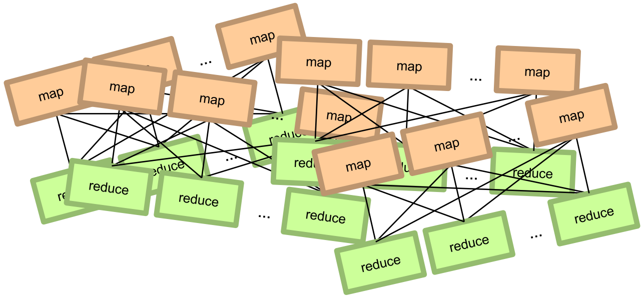
SQL

Aside: Why not just use a database?



YAHOO!

Pig Scripts



Both open-source projects today!

Story for another day….

facebook®

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."

Pig!

Source: Wikipedia (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 Slides adapted from Olston et al. (SIGMOD 2008)

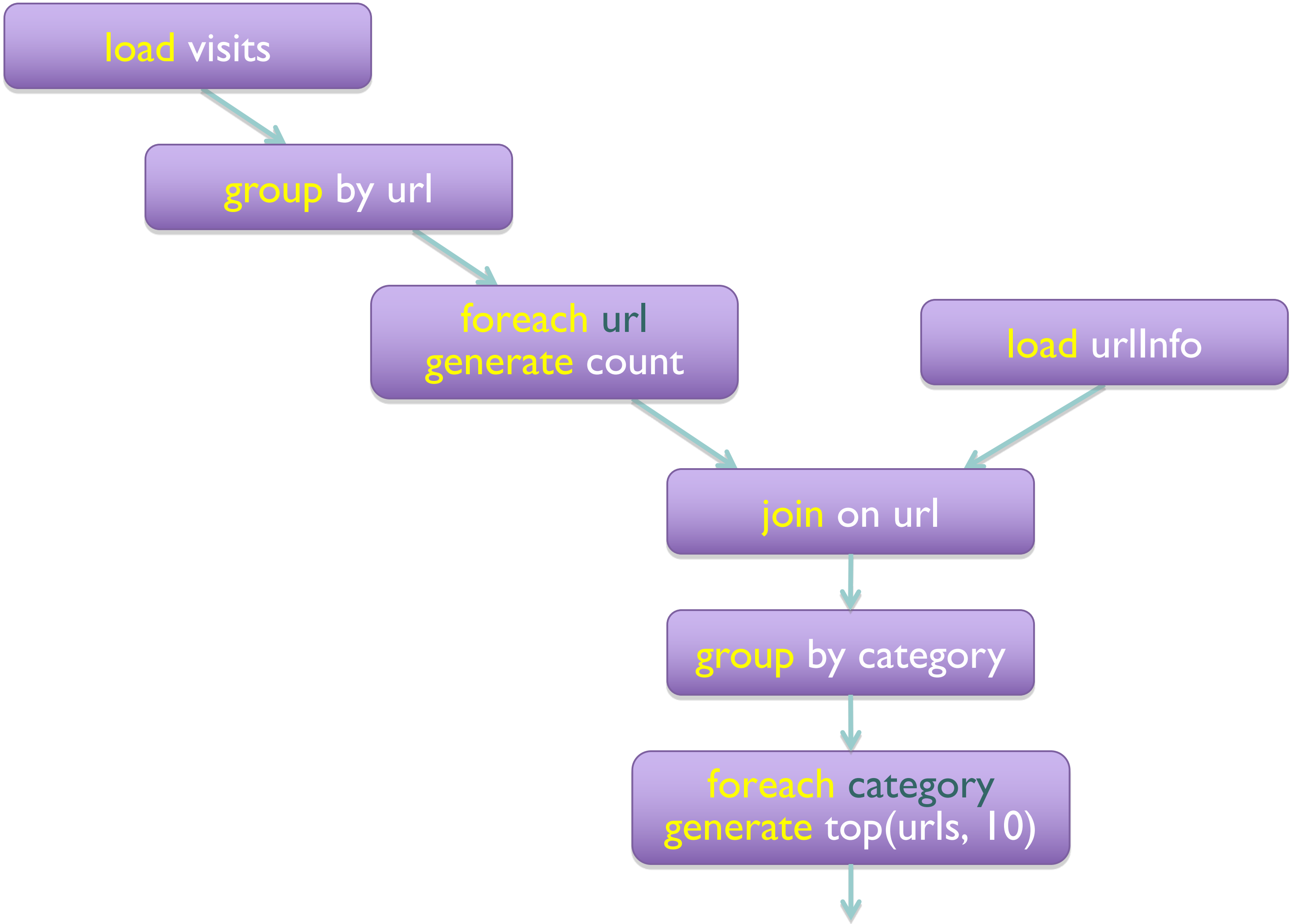
Pig: Example Script

```
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 Slides adapted from Olston et al. (SIGMOD 2008)

Pig Query Plan



load visits

group by url

foreach url
generate count

load urlInfo

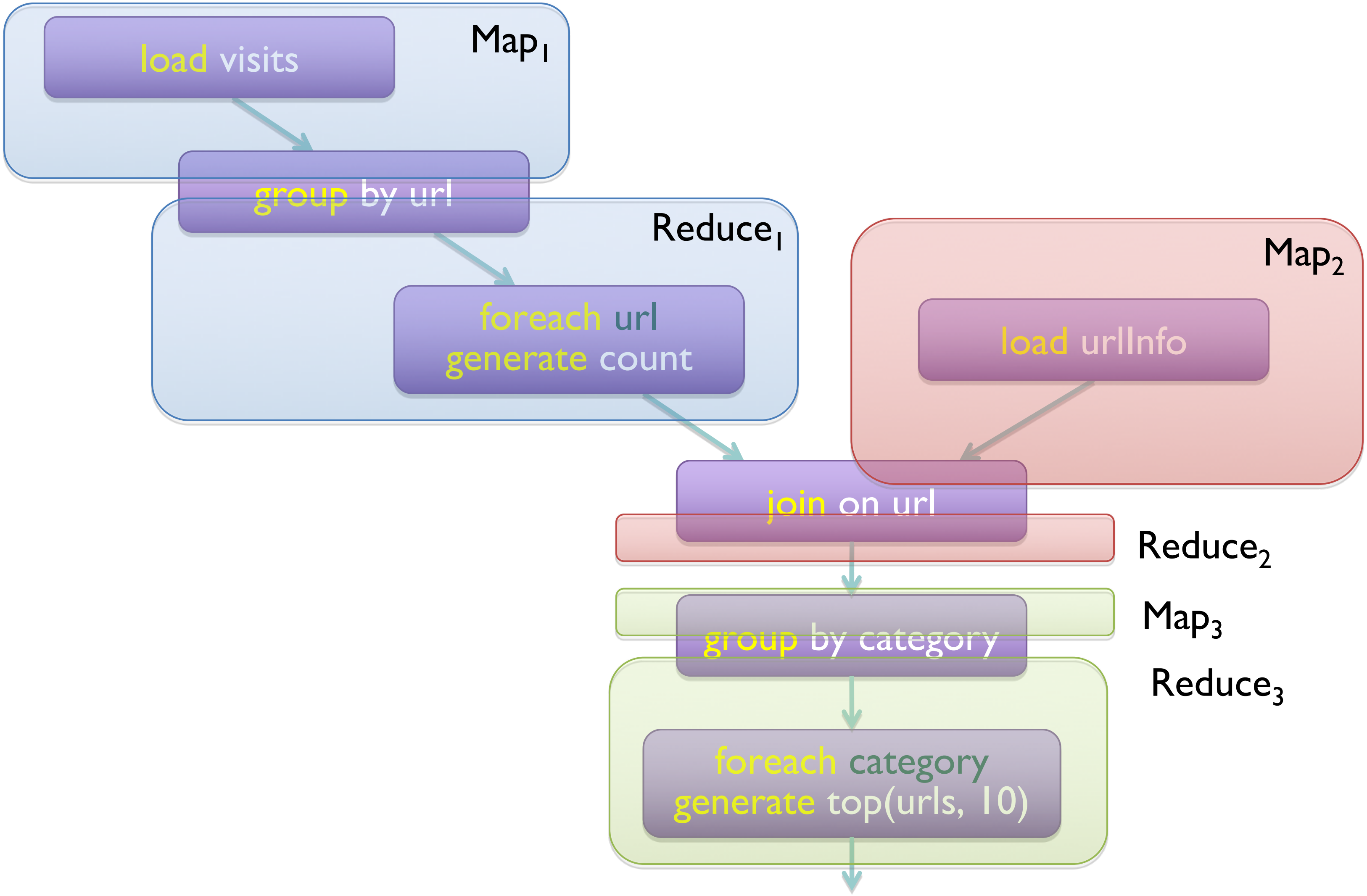
join on url

group by category

foreach category
generate top(urls, 10)

Pig Slides adapted from Olston et al. (SIGMOD 2008)

Pig: MapReduce Execution



Pig Slides adapted from Olston et al. (SIGMOD 2008)

```
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’;
```

This?

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.io.Writable;
i mport org.apache.hadoop.io.WritableComparable;
import org.apache.hadoop.mapred.FileInputFormat;
import org.apache.hadoop.mapred.FileOutputFormat;
import org.apache.hadoop.mapred.JobConf;
import org.apache.hadoop.mapred.KeyValueTextInputFormat;
import org.a     pache.hadoop.mapred.Mapper;
import org.apache.hadoop.mapred.MapReduceBase;
import org.apache.hadoop.mapred.OutputCollector;
import org.apache.hadoop.mapred.RecordReader;
import org.apache.hadoop.mapred.Reducer;
import org.apache.hadoop.mapred.Reporter;
imp ort 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.sub             string(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 w              e know which file
            // it came from.
            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
store it
```

```
                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, Text, LongWritable> {

        public void map(
                Text k,
                Text val,
                OutputColle          ctor<Text, LongWritable> oc,
                Reporter reporter) throws IOException {
            // Find the url
            String line = val.toString();
            int firstComma = line.indexOf(',');
            int secondComma = line.indexOf(',', first                  Comma);
            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 ke       y,
                Iterator<LongWritable> iter,
                OutputCollector<WritableComparable, Writable> oc,
                Reporter reporter) throws IOException {
            // Add up all the values we see

            long sum = 0;
            wh    ile (iter.hasNext()) {
                sum += iter.next().get();
                reporter.setStatus("OK");
            }

            oc.collect(key, new LongWritable(sum));
        }
    }
    public static class LoadClicks extends MapReduceBase
        i   mplements 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
```

```
        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.s     etJobName("Load and Filter Users");
        lfu.setInputFormat(TextInputFormat.class);
        lfu.setOutputKeyClass(Text.class);
        lfu.setOutputValueClass(Text.class);
        lfu.setMapperClass(LoadAndFilterUsers.class);
        FileInputFormat.add          InputPath(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(             MRExample.class);
        join.setJobName("Join Users and Pages");
        join.setInputFormat(KeyValueTextInputFormat.class);
        join.setOutputKeyClass(Text.class);
        join.setOutputValueClass(Text.class);
        join.setMapperClass(IdentityMap               per.class);
        join.setReducerClass(Join.class);
        FileInputFormat.addInputPath(join, new
Path("/user/gates/tmp/indexed_pages"));
        FileInputFormat.addInputPath(join, new
Path("/user/gates/tmp/filtered_users"));
        FileOutputFormat.se          tOutputPath(join, new
Path("/user/gates/tmp/joined"));
        join.setNumReduceTasks(50);
        Job joinJob = new Job(join);
        joinJob.addDependingJob(loadPages);
        joinJob.addDependingJob(loadUsers);

        JobConf group = new JobConf(MRE               xample.class);
        group.setJobName("Group URLs");
        group.setInputFormat(KeyValueTextInputFormat.class);
        group.setOutputKeyClass(Text.class);
        group.setOutputValueClass(LongWritable.class);
        group.setOutputFormat(SequenceFi                leOutputFormat.class);
        group.setMapperClass(LoadJoined.class);
        group.setCombinerClass(ReduceUrls.class);
        group.setReducerClass(ReduceUrls.class);
        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(MRExample.class);
         top100.setJobName("Top 100 sites");
        top100.setInputFormat(SequenceFileInputFormat.class);
        top100.setOutputKeyClass(LongWritable.class);
        top100.setOutputValueClass(Text.class);
        top100.setOutputFormat(SequenceFileOutputF                    ormat.class);
        top100.setMapperClass(LoadClicks.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/top100sitesforusers18to25"));
        top100.setNumReduceTasks(1);
        Job limit = new Job(top100);
        limit.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:                                 B:
(1, 2, 3)                          (2, 4)
(4, 2, 1)                          (8, 9)
(8, 3, 4)                          (1, 3)
(4, 3, 3)                          (2, 7)
(7, 2, 5)                          (2, 9)
(8, 4, 3)                          (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

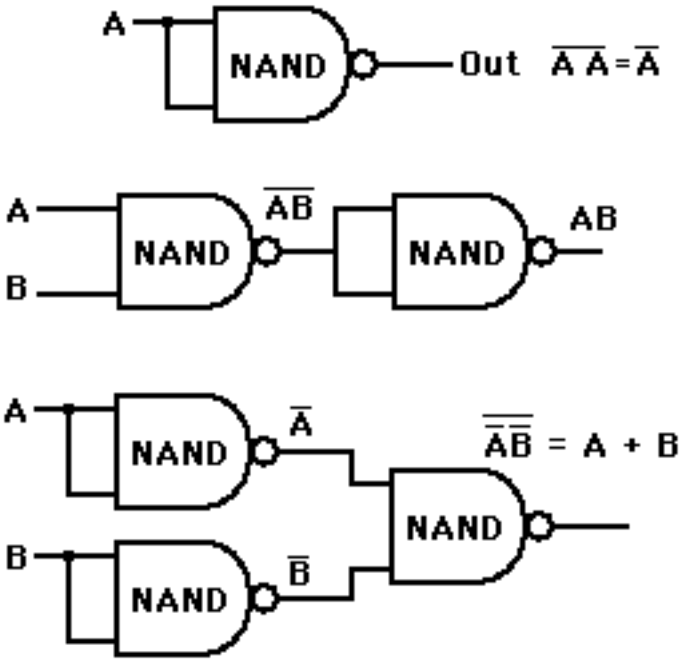
The datacenter *is* the computer!

What's the instruction set?

Okay, let's fix this!

Source: Google

Analogy: NAND Gates are universal


A
NAND
Out
$\overline{A\,A} = \overline{A}$
A
B
NAND
$\overline{AB}$
NAND
AB
A
NAND
$\overline{A}$
B
NAND
$\overline{B}$
NAND
$\overline{\overline{A}\,\overline{B}} = A + B$

Let’s design a data processing language “from scratch”!

What ops do you need?

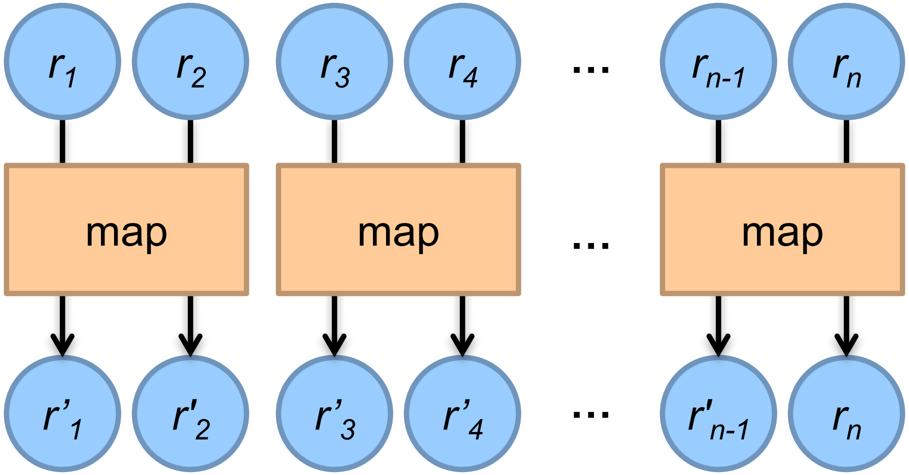
(Why is MapReduce the way it is?)

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

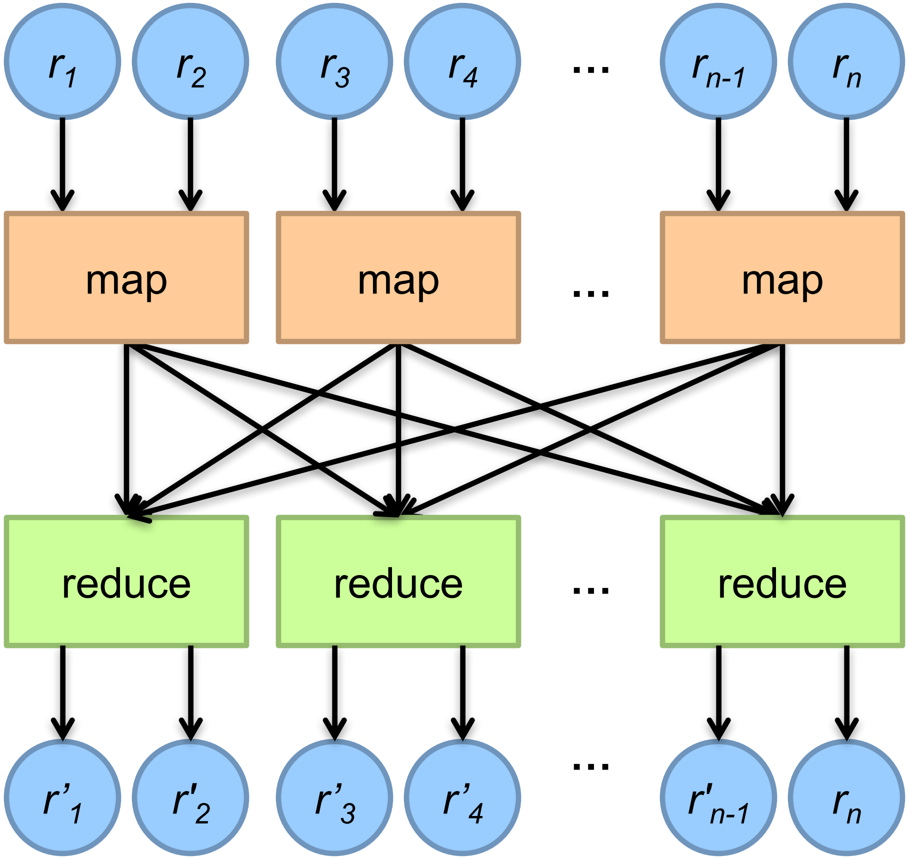
Map alone isn’t enough

(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?

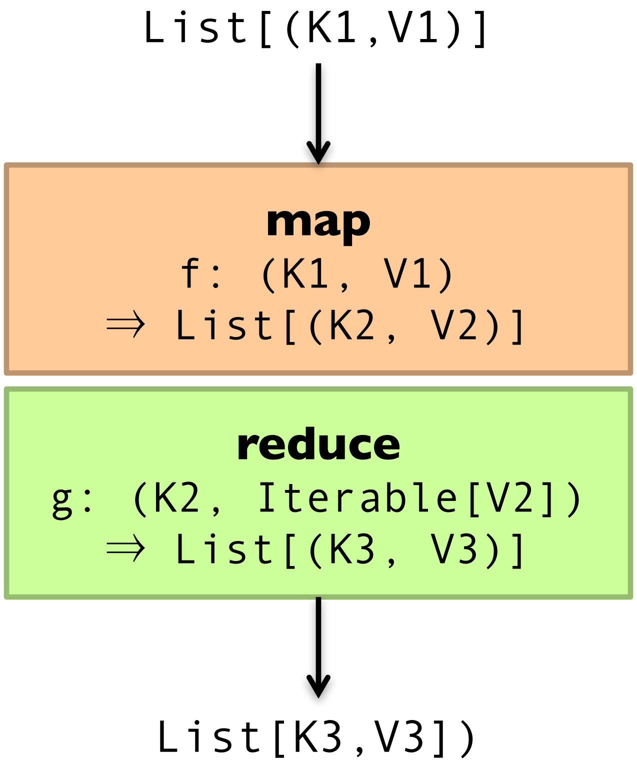
Once we resolve the addressing, apply another computation
That’s what we call reduce!
(What’s with the sorting then?)

MapReduce



MapReduce is the minimally “interesting” dataflow!

MapReduce



List[(K1,V1)]

map

f: (K1, V1)

⇒ List[(K2, V2)]

reduce

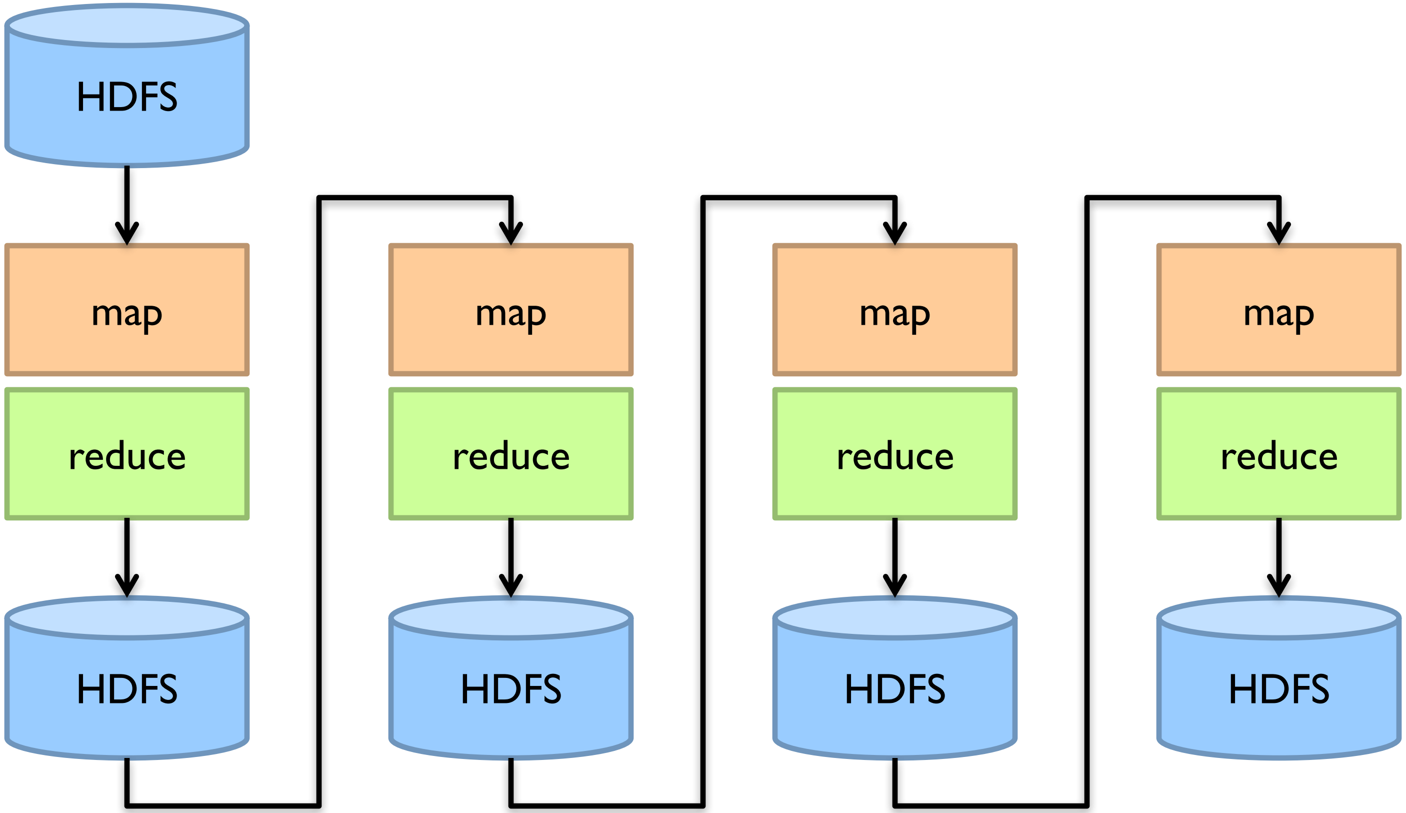
g: (K2, Iterable[V2])

⇒ List[(K3, V3)]

List[K3,V3])

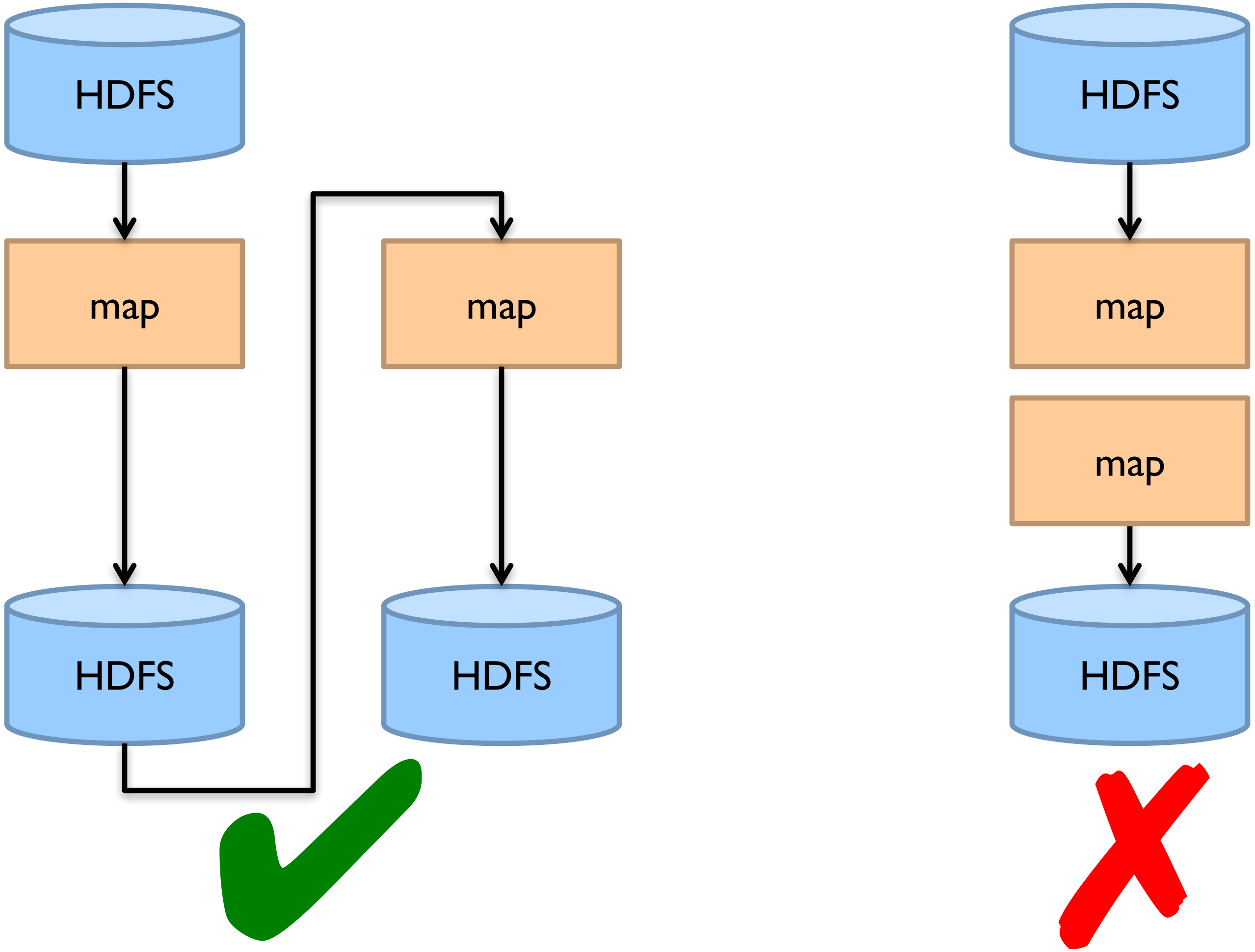
(note we’re abstracting the “data-parallel” part)

MapReduce Workflows

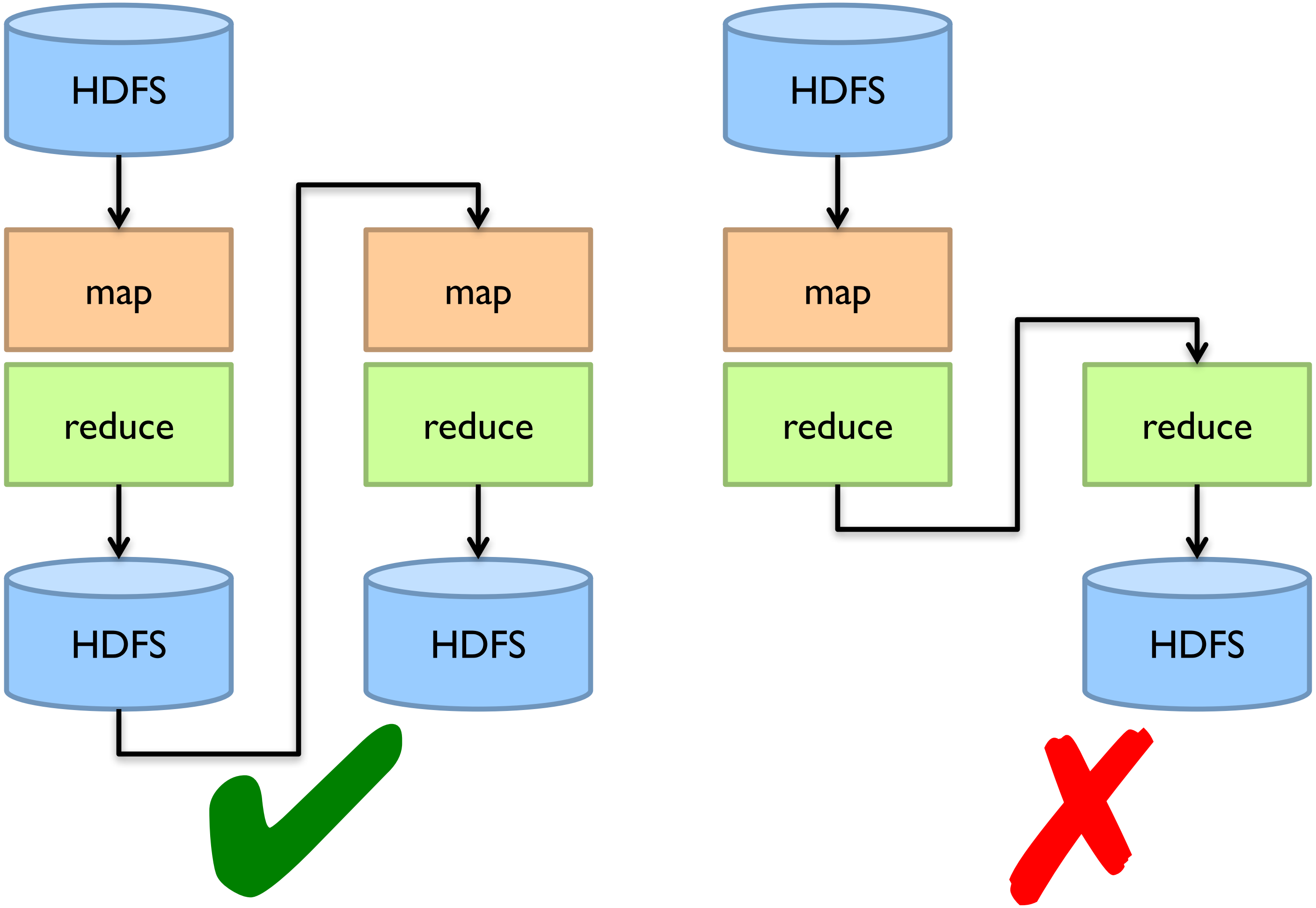


What's wrong?

Want MM?



Want MRR?

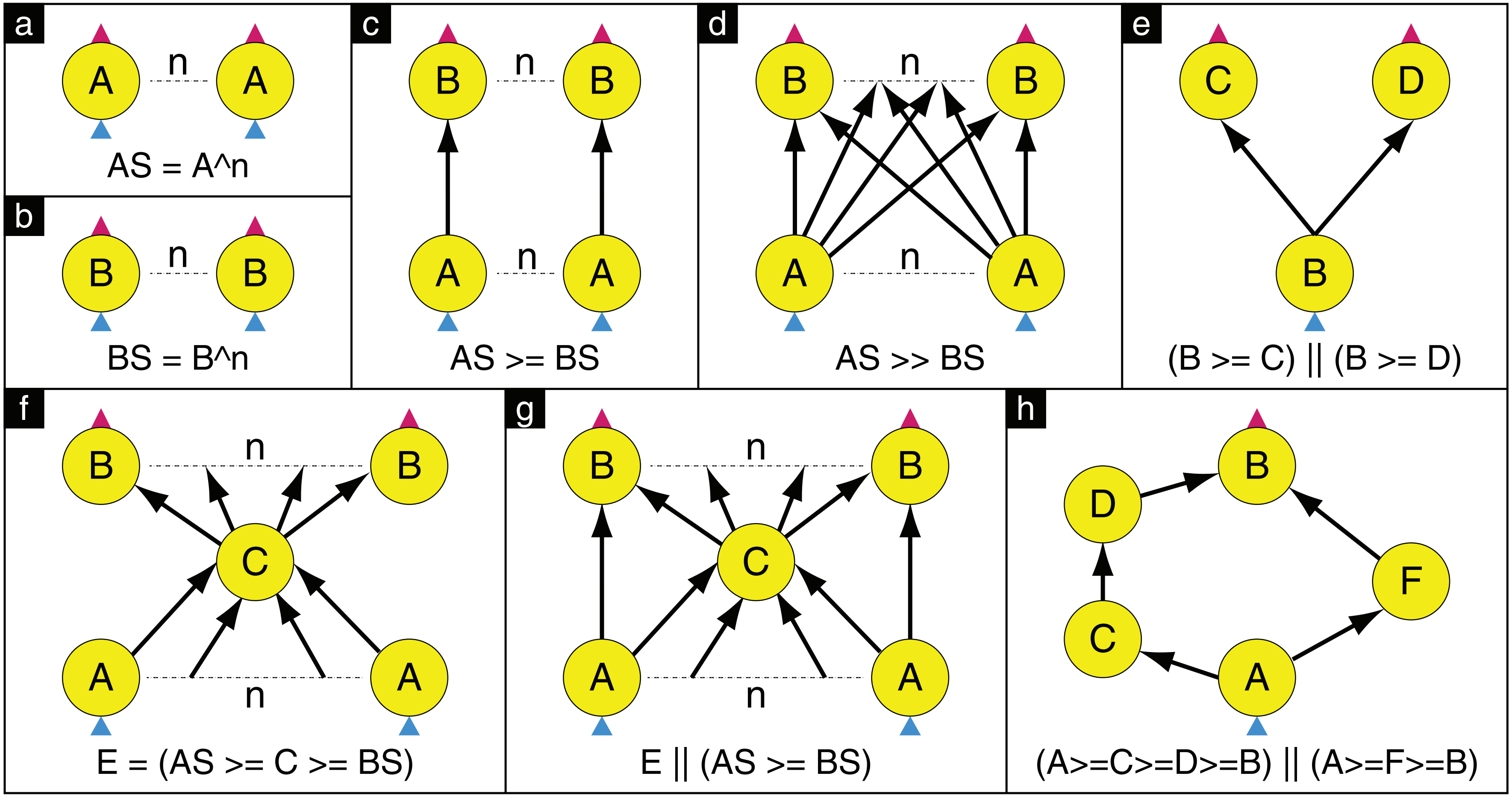

HDFS
map
reduce
HDFS
map
reduce
HDFS
✓
HDFS
map
reduce
reduce
HDFS
✗

The datacenter *is* the computer!

Let’s enrich the instruction set!

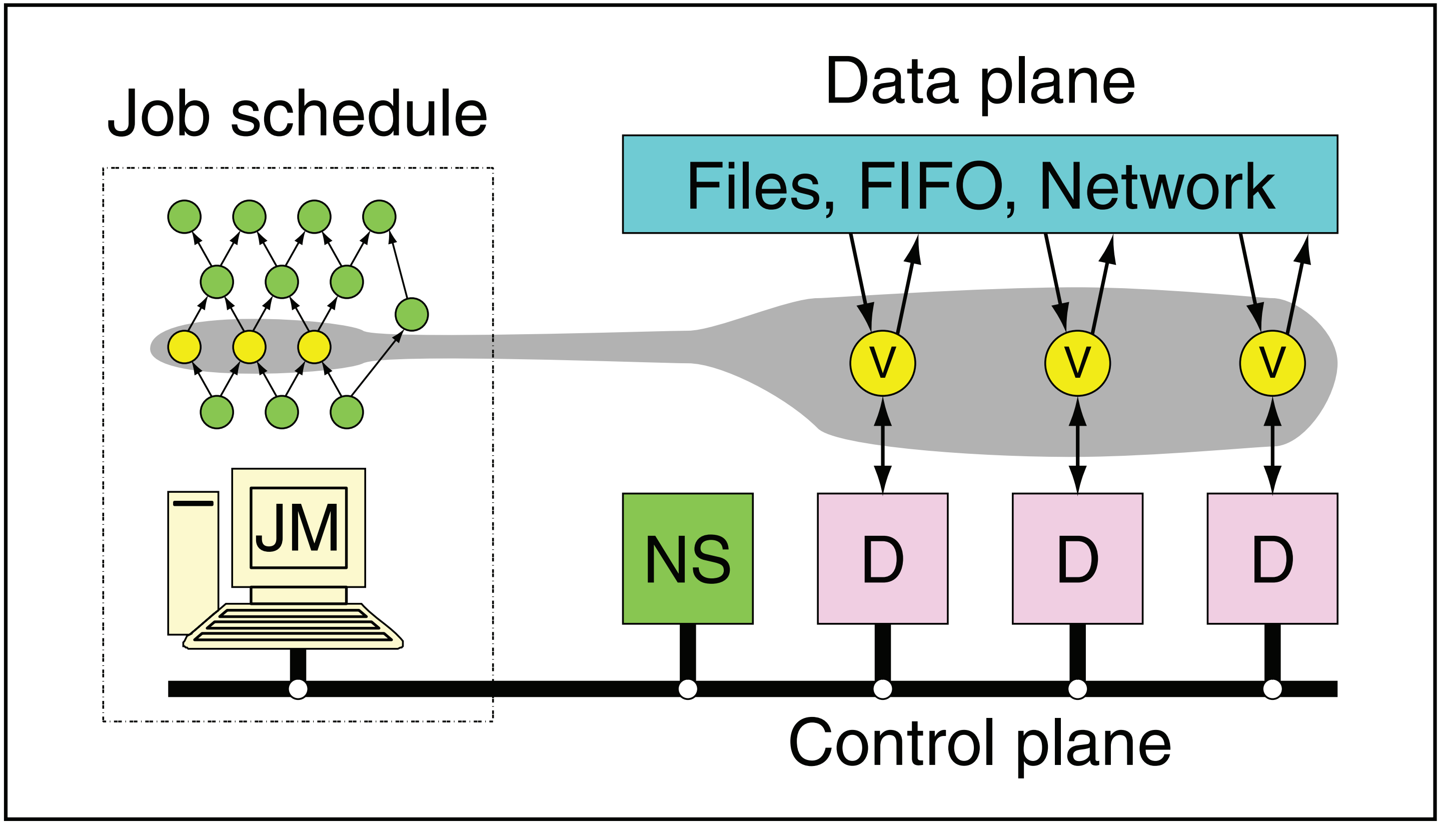
Source: Google

Dryad: Graph Operators



Source: Isard et al. (2007) Dryad: Distributed Data-Parallel Programs from Sequential Building Blocks. EuroSys.

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.

Source: Isard et al. (2007) Dryad: Distributed Data-Parallel Programs from Sequential Building Blocks. EuroSys.

Dryad: Cool Tricks

Channel: abstraction for vertex-to-vertex communication

File

TCP pipe

Shared memory

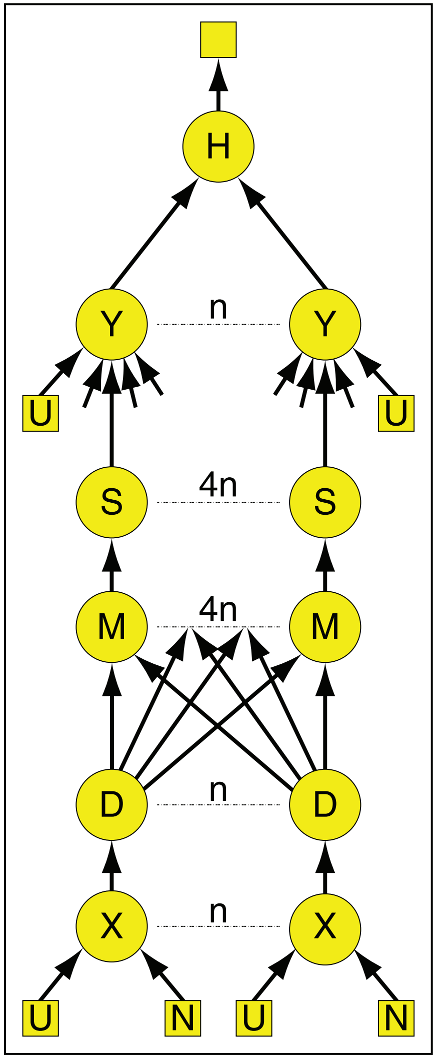
Runtime graph refinement

Size of input is not known until runtime

Automatically rewrite graph based on invariant properties

Source: Isard et al. (2007) Dryad: Distributed Data-Parallel Programs from Sequential Building Blocks. EuroSys.

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;
```

Source: Isard et al. (2007) Dryad: Distributed Data-Parallel Programs from Sequential Building Blocks. EuroSys.

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?

Source: Yu et al. (2008) DryadLINQ: A System for General-Purpose Distributed Data-Parallel Computing Using a High-Level Language. OSDI.

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);
```

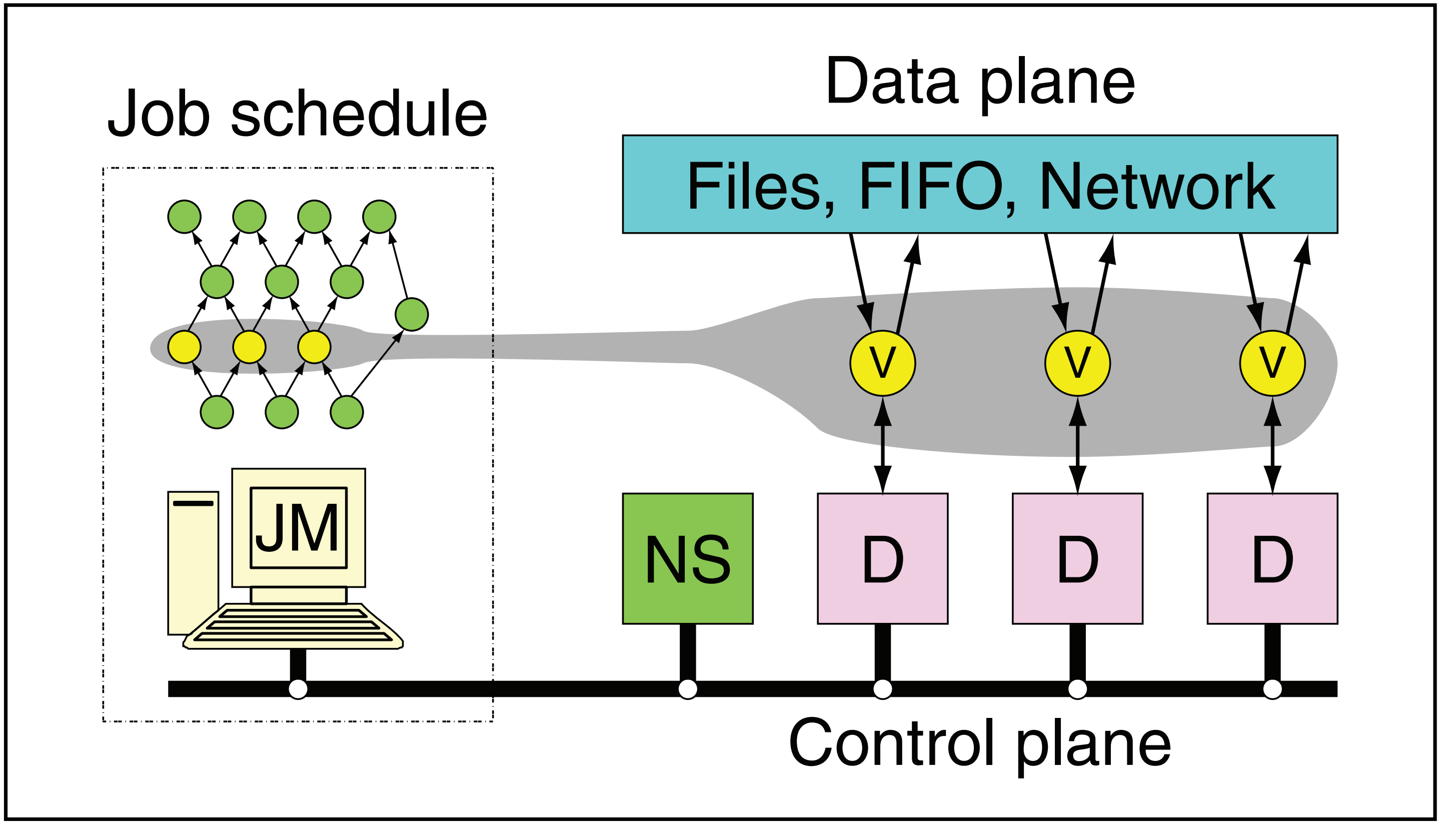
Compare:

```
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?



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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:

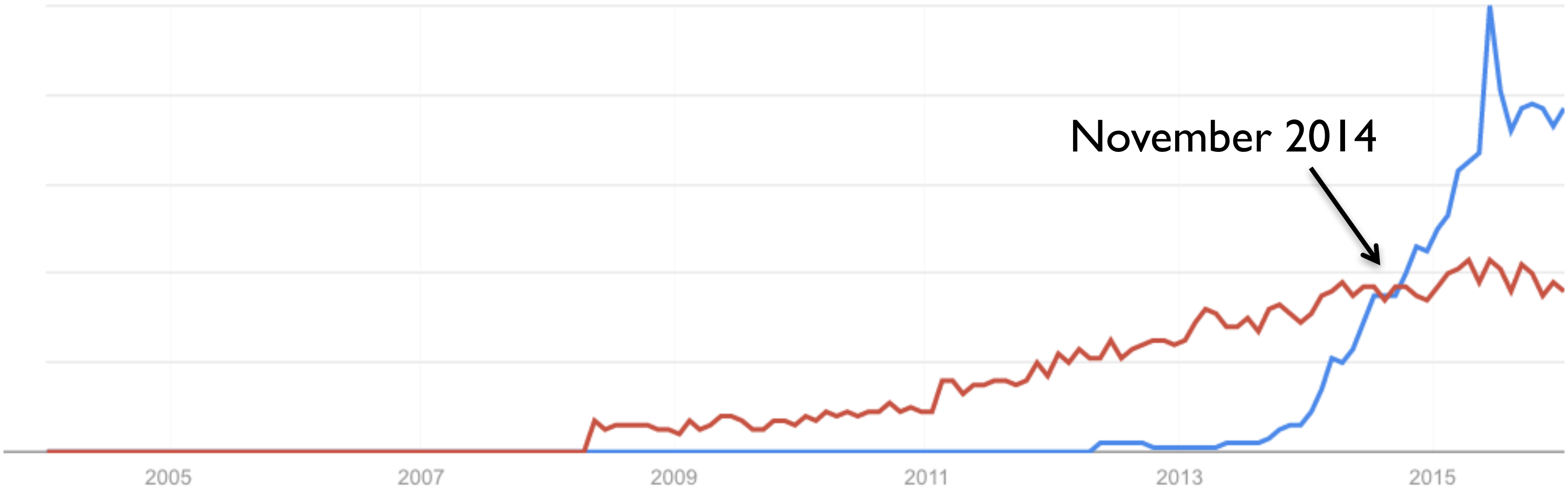
Developed at UC Berkeley AMPLab in 2009

Open-sourced in 2010

Became top-level Apache project in February 2014

Commercial support provided by DataBricks

Spark vs. Hadoop



November 2014

Google Trends

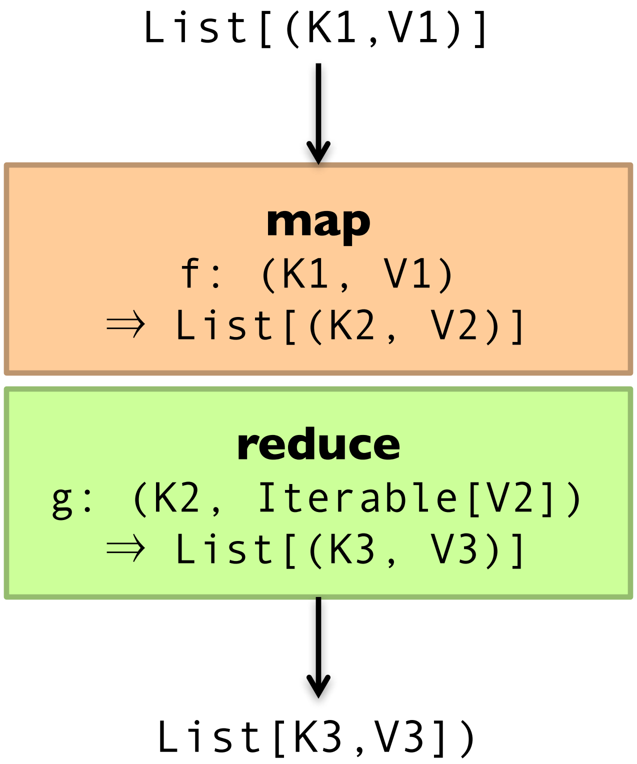
Source: Datanami (2014): http://www.datanami.com/2014/11/21/spark-just-passed-hadoop-popularity-web-heres/

What’s an RDD?

Resilient Distributed Dataset (RDD)

Much more next session…

MapReduce



List[(K1,V1)]

map

f: (K1, V1)

⇒ List[(K2, V2)]

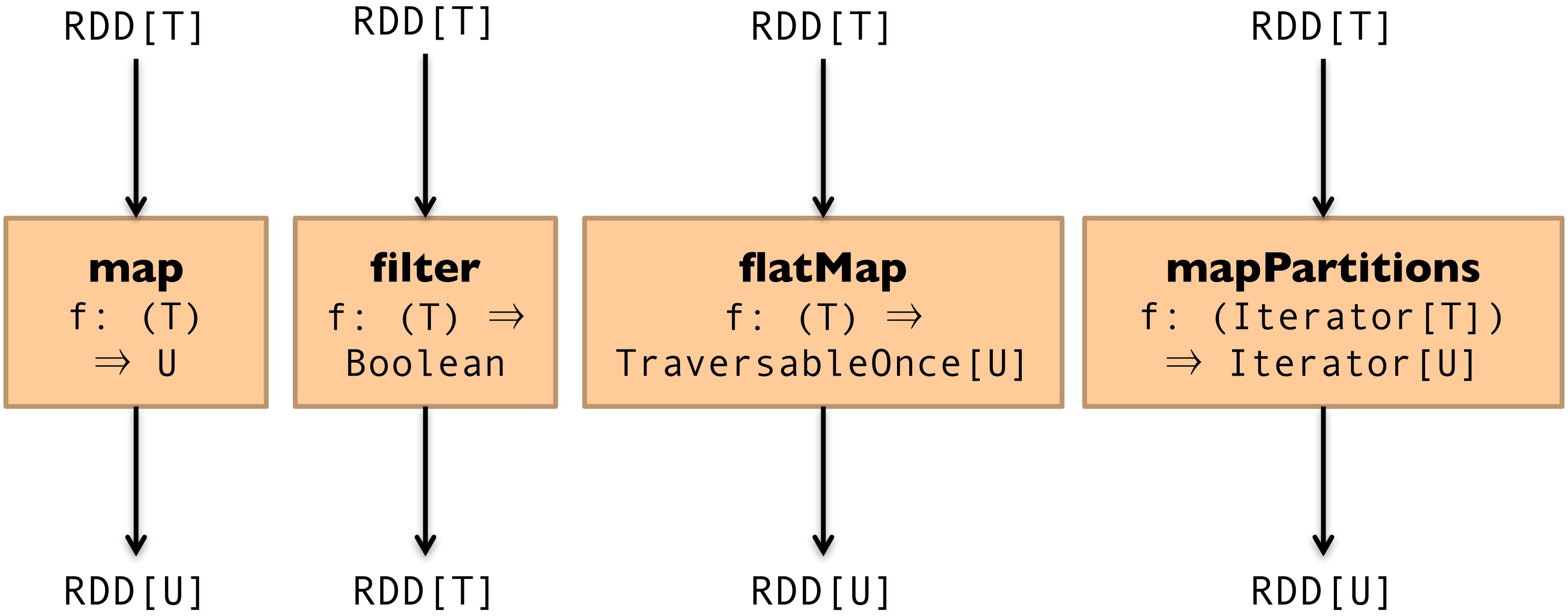
reduce

g: (K2, Iterable[V2])

⇒ List[(K3, V3)]

List[K3,V3])

Map-like Operations



RDD[T] → **map** f: (T) ⇒ U → RDD[U]

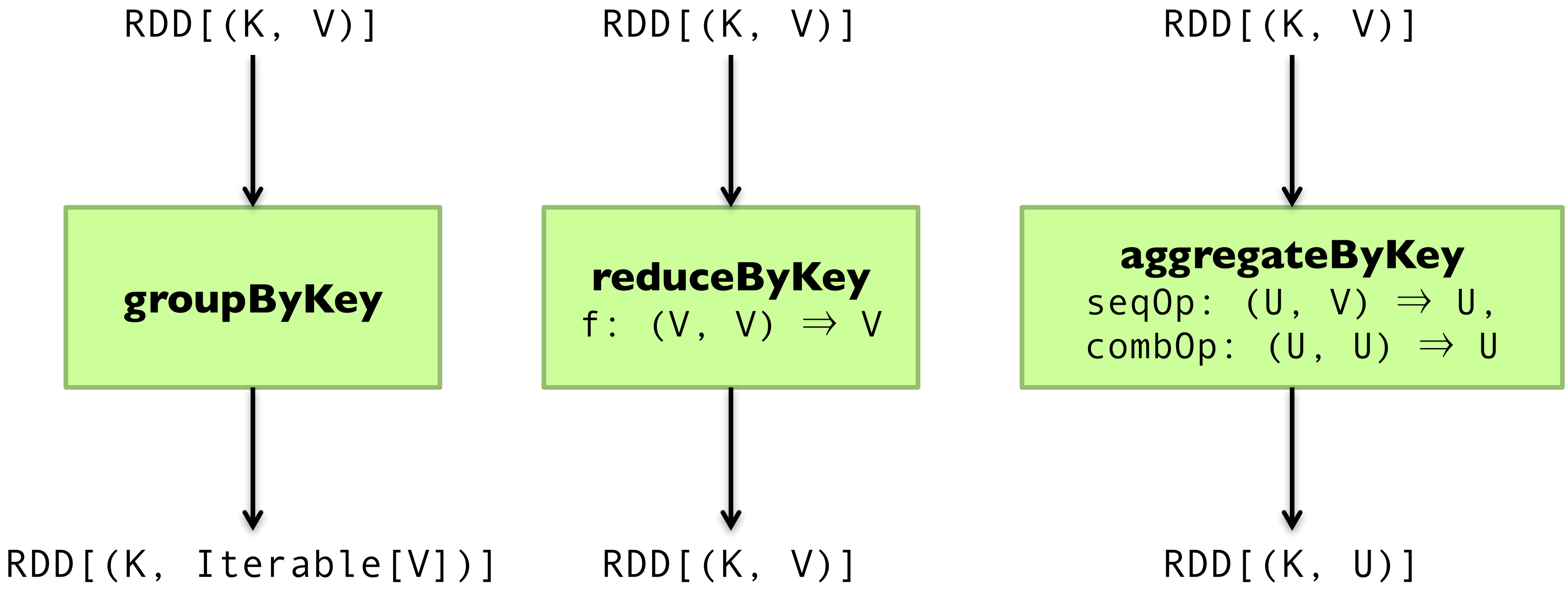
RDD[T] → **filter** f: (T) ⇒ Boolean → RDD[T]

RDD[T] → **flatMap** f: (T) ⇒ TraversableOnce[U] → RDD[U]

RDD[T] → **mapPartitions** f: (Iterator[T]) ⇒ Iterator[U] → RDD[U]

(Not meant to be exhaustive)

Reduce-like Operations



`RDD[(K, V)]`

groupByKey

`RDD[(K, Iterable[V])]`

`RDD[(K, V)]`

reduceByKey
`f: (V, V) ⇒ V`

`RDD[(K, V)]`

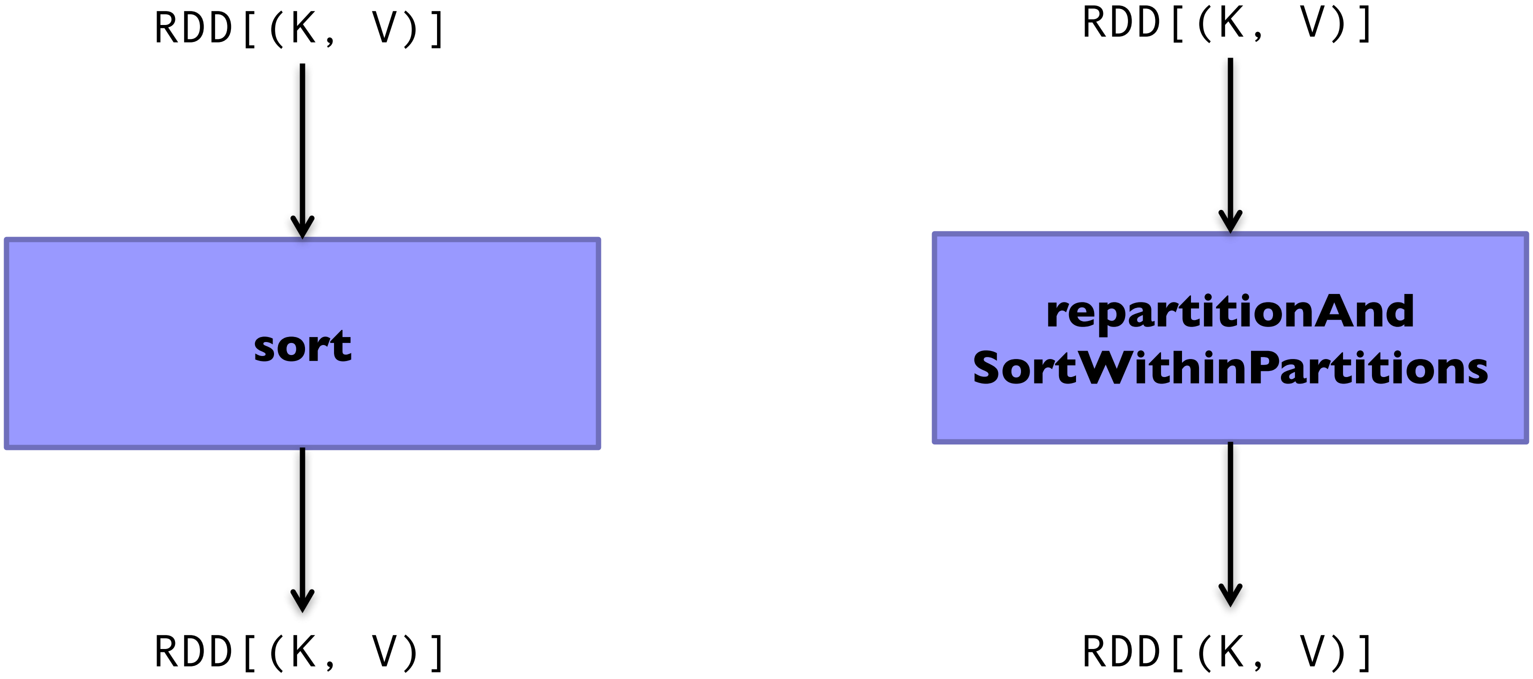
`RDD[(K, V)]`

aggregateByKey
`seqOp: (U, V) ⇒ U,`
`combOp: (U, U) ⇒ U`

`RDD[(K, U)]`

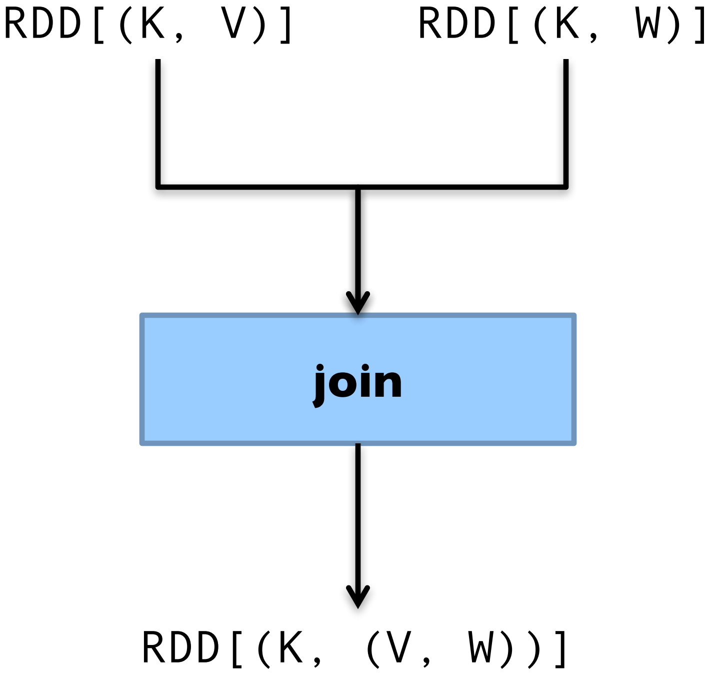
(Not meant to be exhaustive)

Sort Operations



(Not meant to be exhaustive)

Join-like Operations

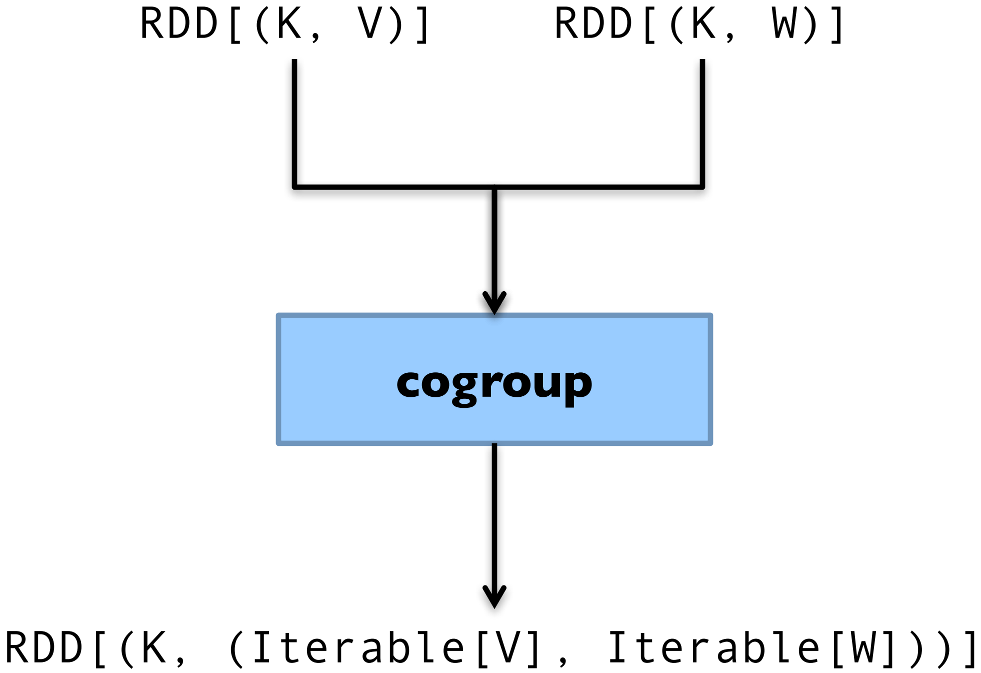


RDD[(K, V)]

RDD[(K, W)]

join

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



RDD[(K, V)]

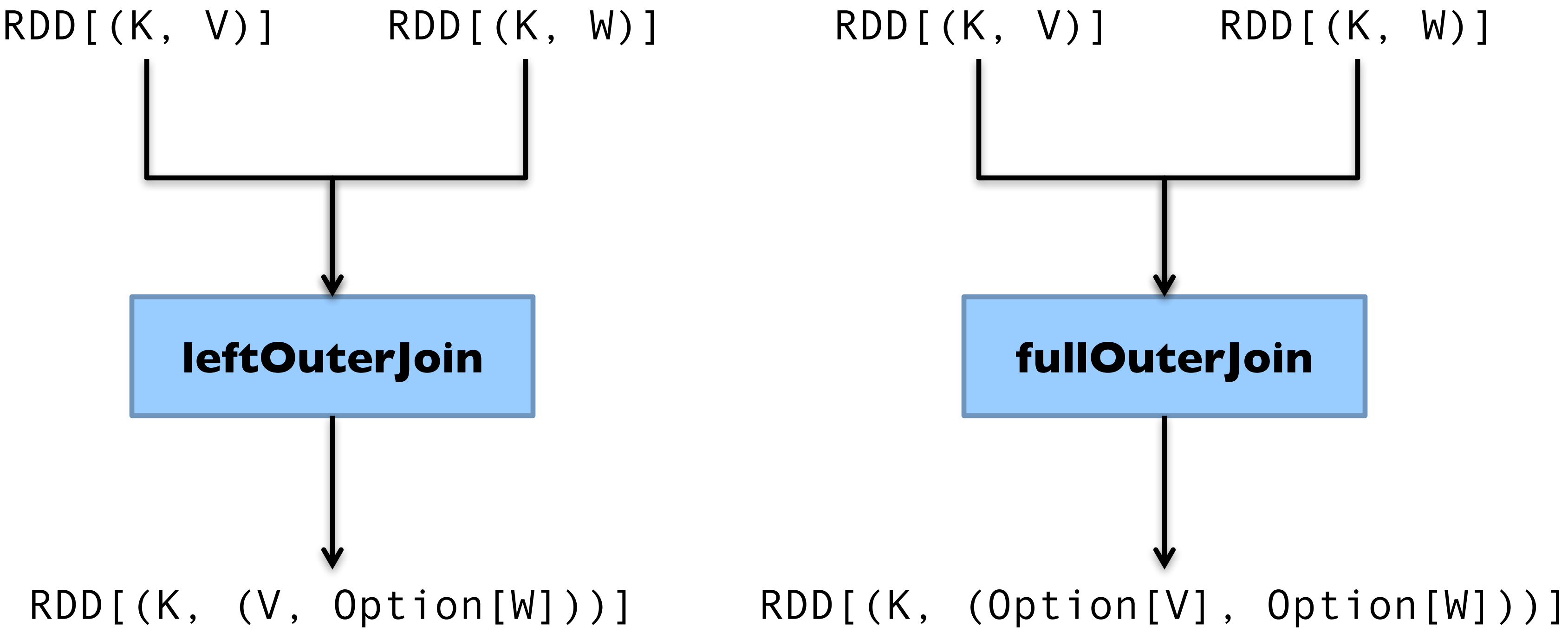
RDD[(K, W)]

cogroup

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

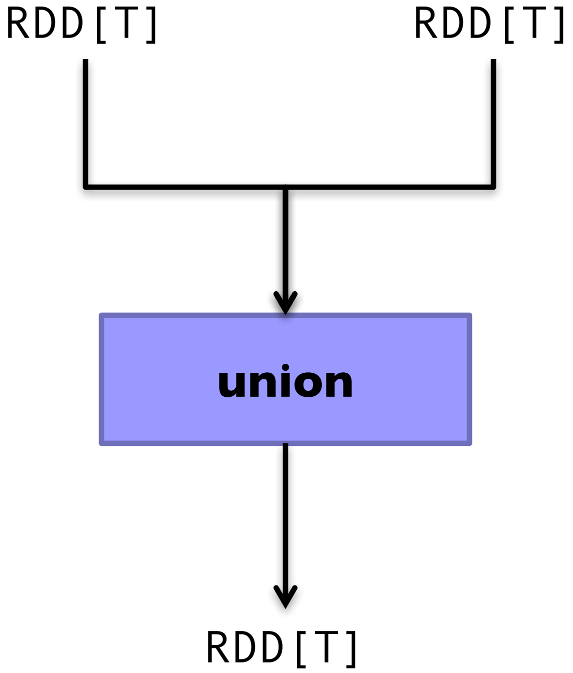
(Not meant to be exhaustive)

Join-like Operations



(Not meant to be exhaustive)

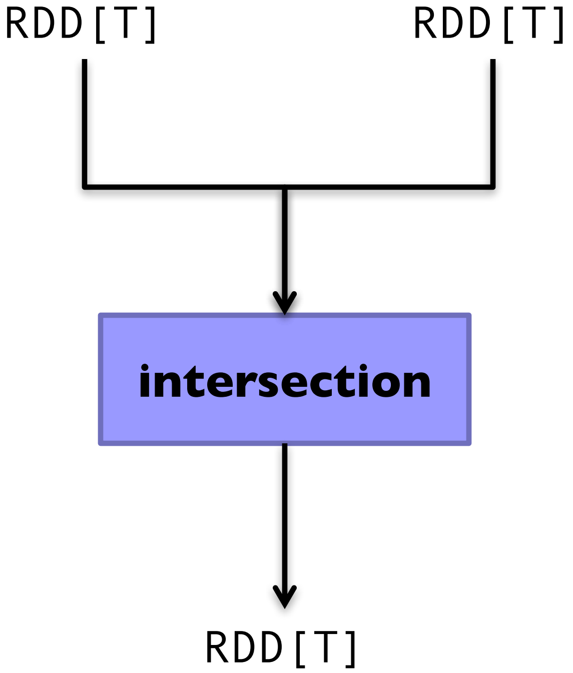
Set-ish Operations


RDD[T]

RDD[T]

union

RDD[T]


RDD[T]

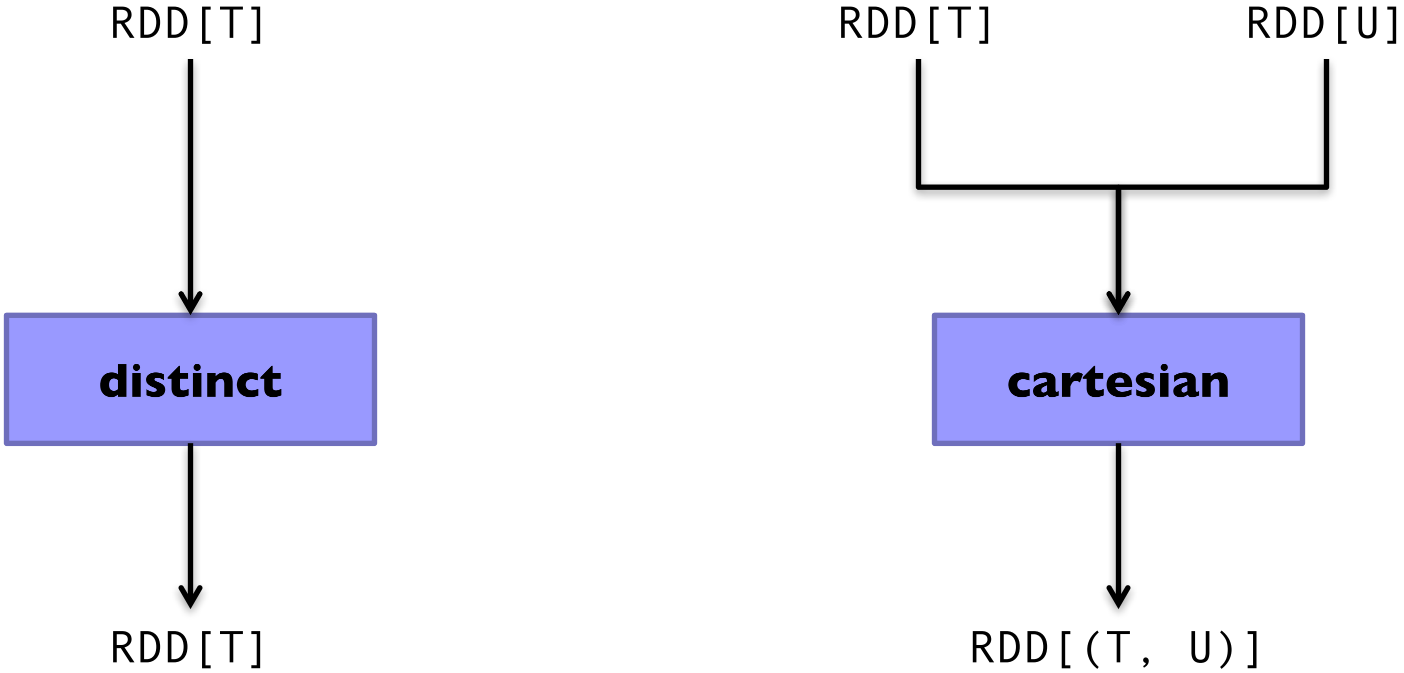
RDD[T]

intersection

RDD[T]

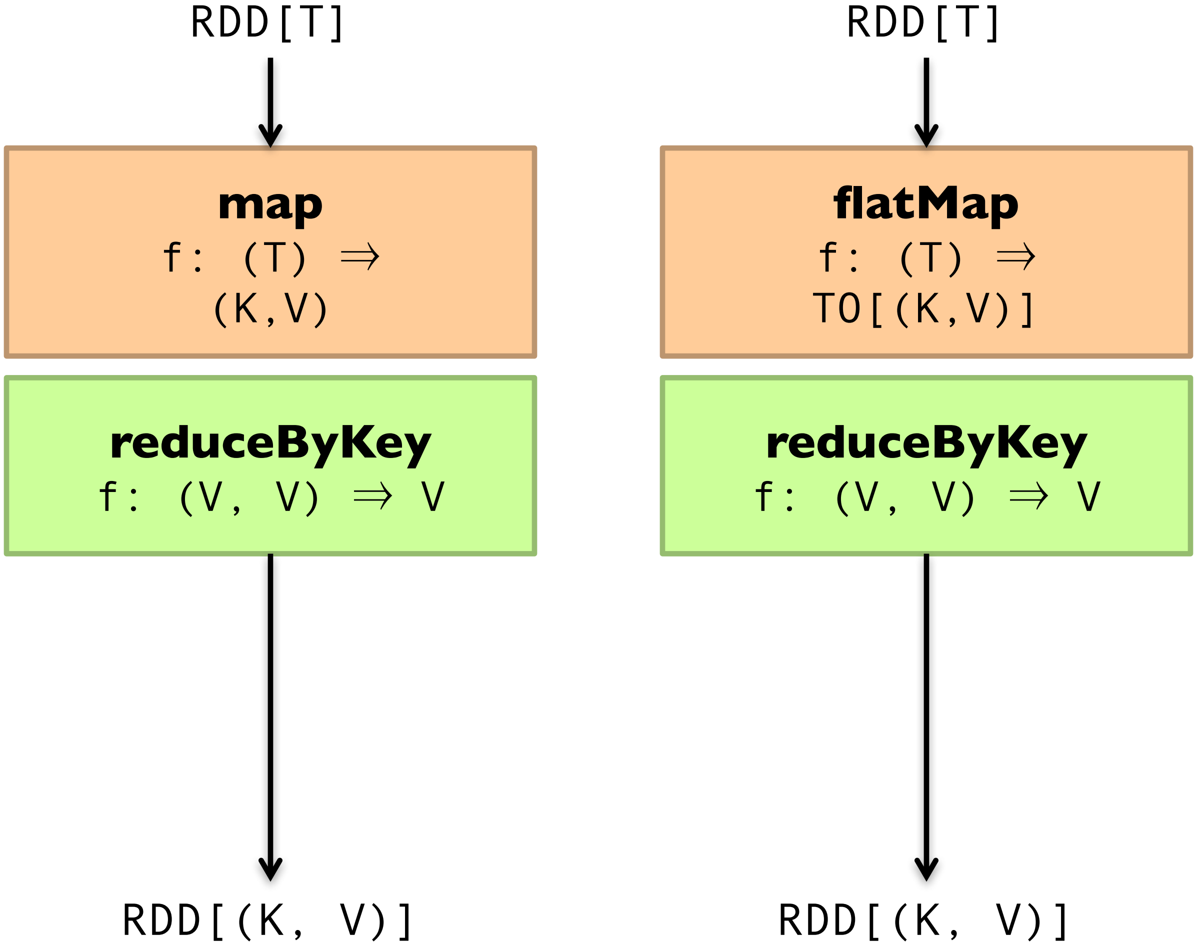
(Not meant to be exhaustive)

Set-ish Operations



(Not meant to be exhaustive)

MapReduce in Spark?



RDD[T]

map
f: (T) ⇒ (K,V)

reduceByKey
f: (V, V) ⇒ V

RDD[(K, V)]

RDD[T]

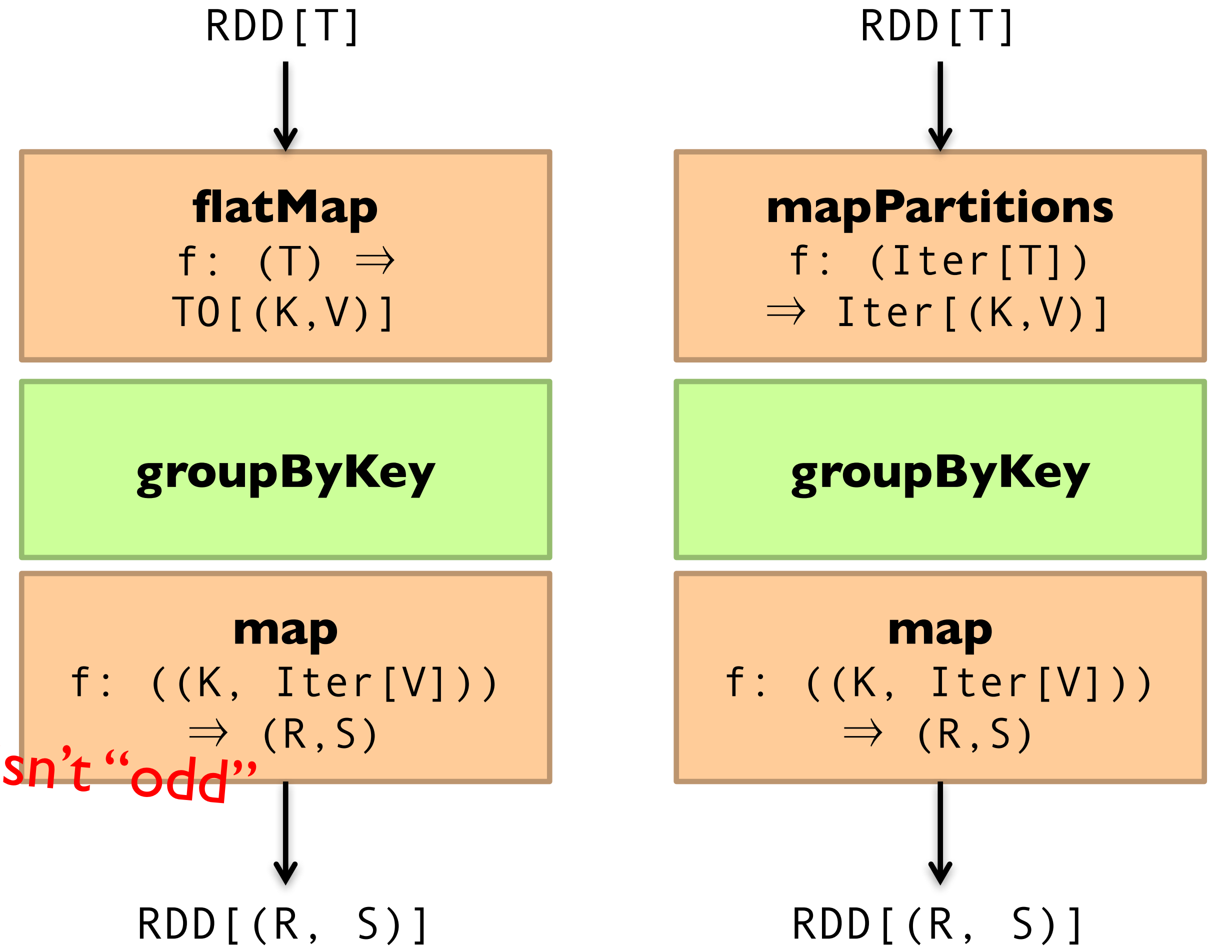
flatMap
f: (T) ⇒ TO[(K,V)]

reduceByKey
f: (V, V) ⇒ V

RDD[(K, V)]

Not quite…

MapReduce in Spark?



RDD[T]

flatMap
f: (T) ⇒
TO[(K,V)]

groupByKey

map
f: ((K, Iter[V]))
⇒ (R,S)

RDD[(R, S)]

RDD[T]

mapPartitions
f: (Iter[T])
⇒ Iter[(K,V)]

groupByKey

map
f: ((K, Iter[V]))
⇒ (R,S)

RDD[(R, S)]

Nope, this isn't "odd"

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) => 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

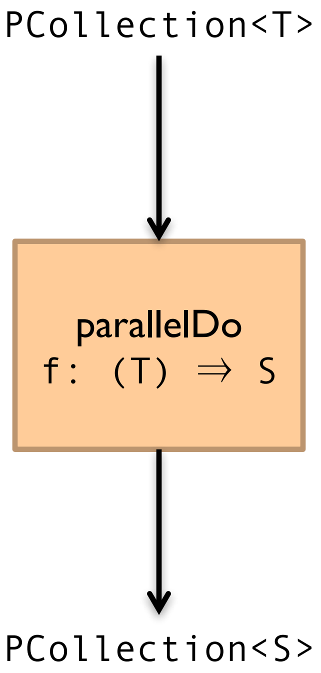
PCollection<T> - a (possibly huge) immutable bag of elements of type T

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

Hmm… sounds suspiciously familiar…

Flume(Java)

Primitive operations

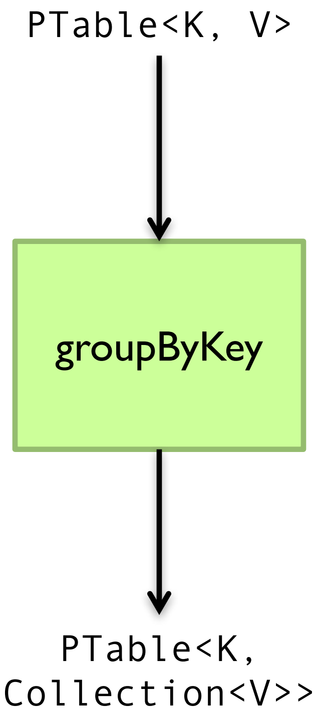


```
PCollection<String> words =
  lines.parallelDo(new DoFn<String,String>() {
    void process(String line, EmitFn<String> emitFn) {
      for (String word : splitIntoWords(line)) {
        emitFn.emit(word);
      }
    }
  }, collectionOf(strings()));
```

Hmm… looks suspiciously familiar…

Flume(Java)

Primitive operations



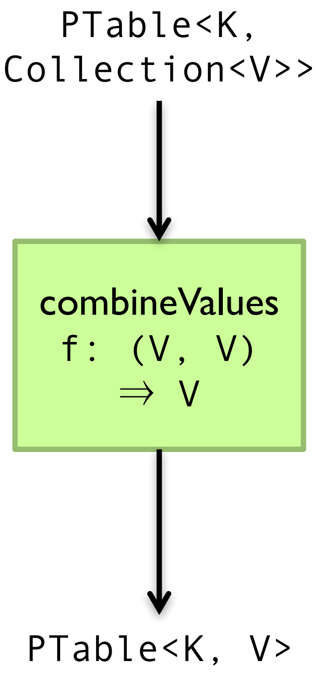
```
PTable<URL,DocInfo> backlinks =
  docInfos.parallelDo(new DoFn<DocInfo, Pair<URL,DocInfo>>() {
    void process(DocInfo docInfo, EmitFn<Pair<URL,DocInfo>> emitFn) {
      for (URL targetUrl : docInfo.getLinks()) {
        emitFn.emit(Pair.of(targetUrl, docInfo));
      }
    }
  }, tableOf(recordsOf(URL.class),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

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

Hmm… looks suspiciously familiar…

Flume(Java)

Primitive operations



PTable<K, Collection<V>>

combineValues
f: (V, V) ⇒ 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 1 due Tuesday 2:30pm

Source: Wikipedia (Japanese rock garden)