# Introduction to MapReduce Algorithms and Analysis

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# Trade-Offs

*Massive parallelism that is very easy to program.*

- Cheaper than HPC style (uses top of the line everything)
- Assumption about data (key-value pairs).
- Restrictions on how computation is done.

# Cluster of Commodity Nodes (2003)

Big Iron Box:

- 8 2GHz Xeons (Processors)
- 64 GB RAM
- 8 TB disk
- 758,000 USD

Google Rack:

- 176 2GHz Xeons (Processors)
- 176 GB RAM
- 7 TB disk
- 278,000 USD

# Google File System

SOSP 2003 (Ghemawat, Gobioff, Leung)

**Key-Value Pairs:**
All files stored as Key-Value pairs

- **key:** log id **value:** actual log
- **key:** web address **value:** html and/or outgoing links
- **key:** document id in set **value:** list of words
- **key:** word in corpus **value:** how often it appears

**Blocking:**
All files broken into blocks (often **64 MB**)
Each block has replication factor (say **3** times), stored in separate nodes.
No locality on compute nodes, no neighbors or replicas on same node (but often same rack).

# No locality?

Really?

# No locality?

Really?

- Resiliency: if one dies, use another
  (on big clusters happens all the time)
- Redundancy: If one is slow, use another
  (...curse of last reducer)
- Heterogeneity: Format quite flexible, 64MB often still enough
  (recall: IO-Efficiency)

# MapReduce

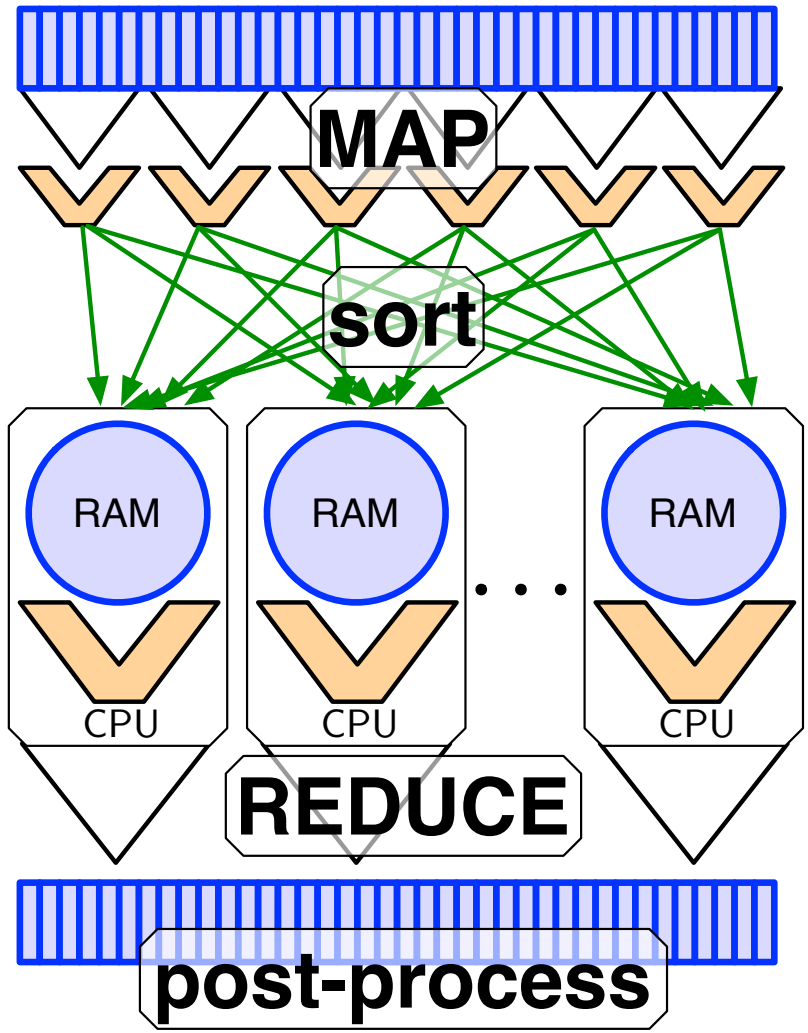
OSDI 04 (Dean, Ghemawat)

Each Processor has full hard drive, data items $< \text{KEY}, \text{VALUE} >$.
Parallelism Procedes in Rounds:

- Map: assigns items to processor by KEY.
- Reduce: processes all items using VALUE. Usually combines many items with same KEY.

**Repeat** M+R a constant number of times, often only one round.

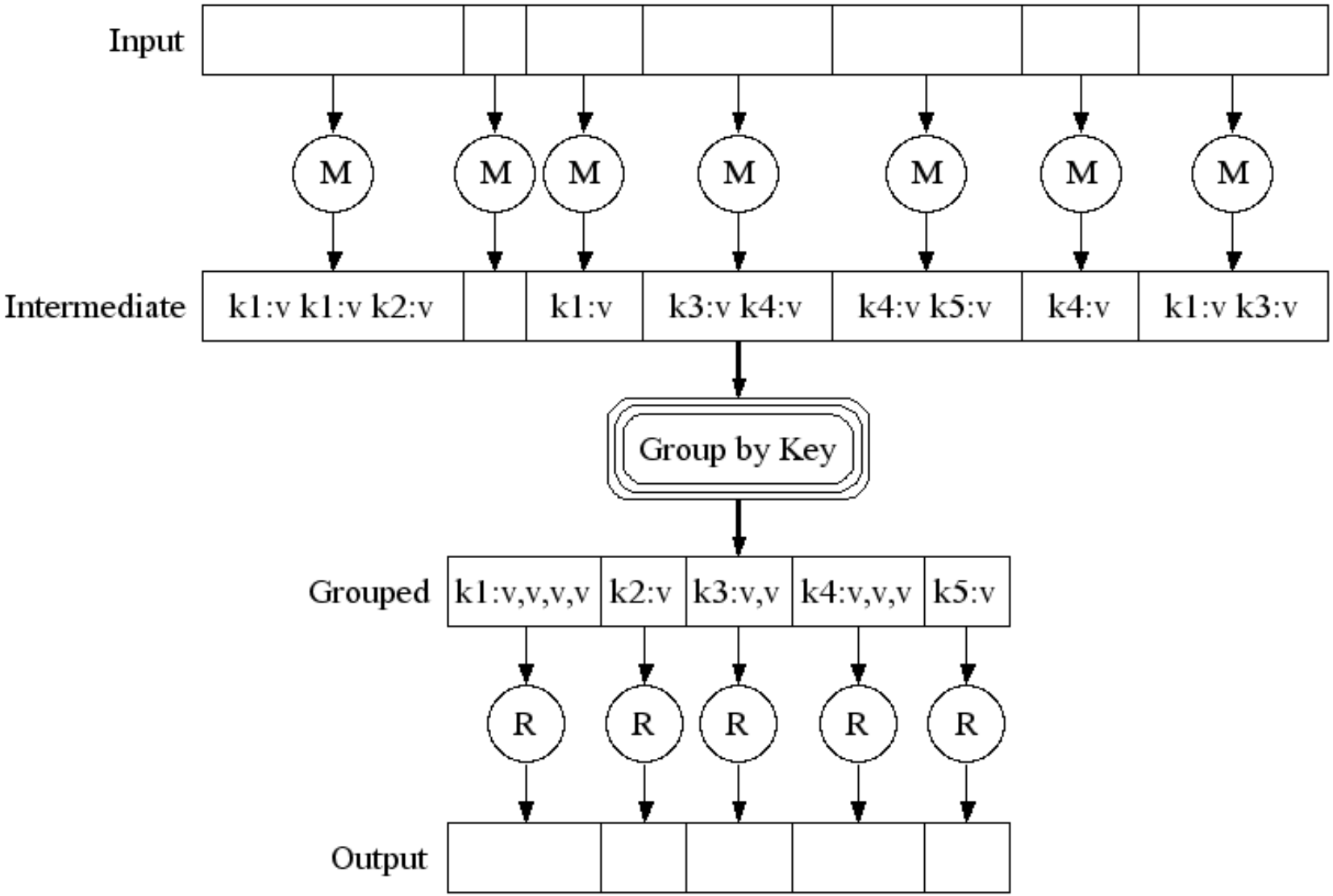
- Optional post-processing step.




Pro: Robust (duplication) and simple. Can harness Locality
Con: Somewhat restrictive model

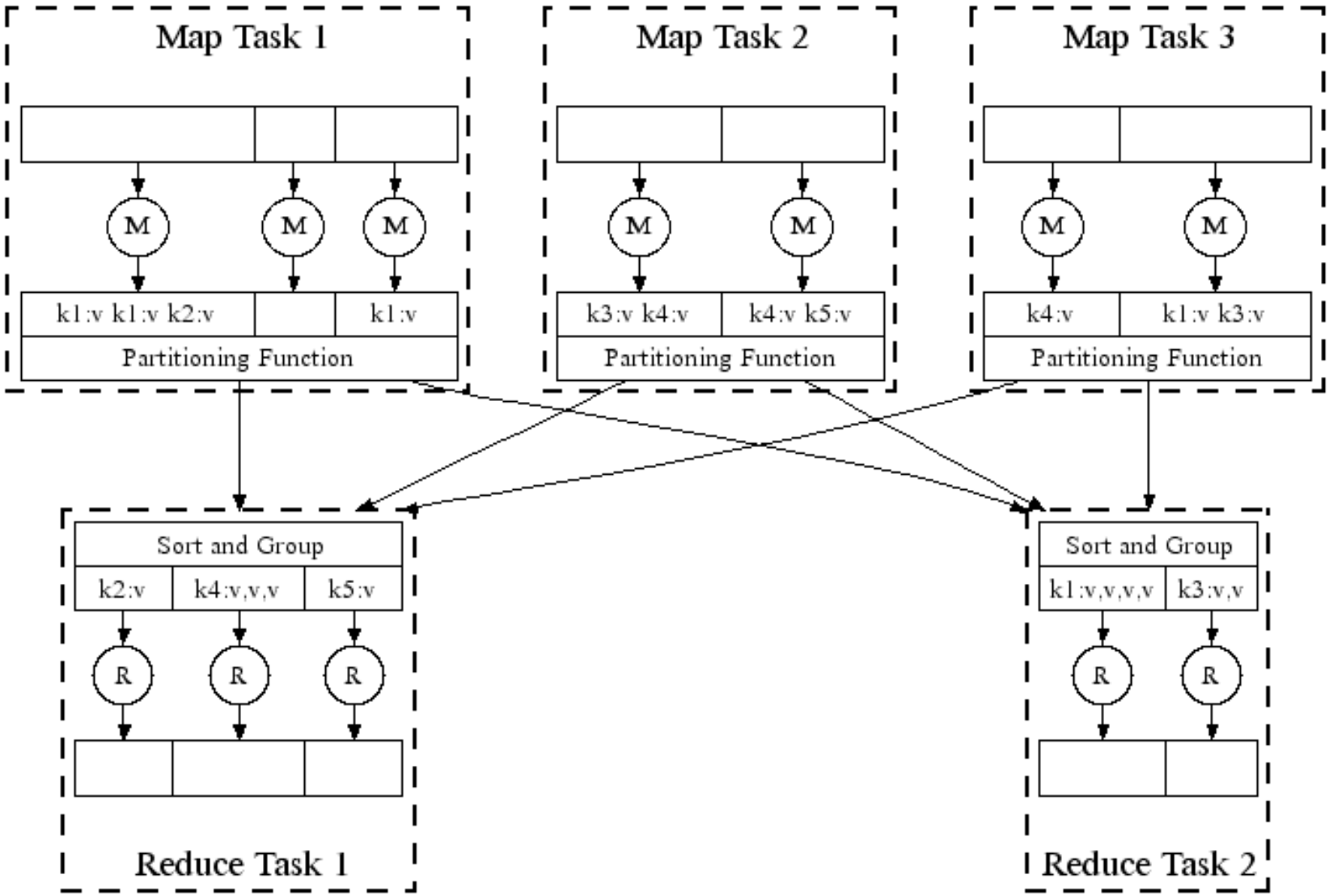
# MapReduce

OSDI 04 (Dean, Ghemawat)



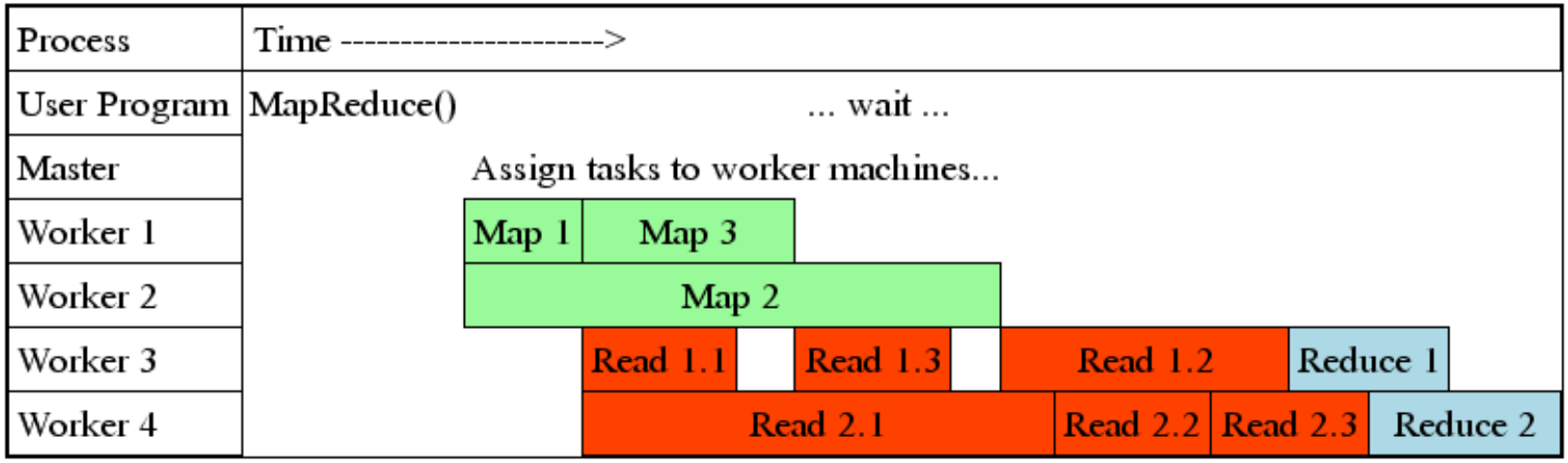
# MapReduce

OSDI 04 (Dean, Ghemawat)



# Granularity and Pipelining

OSDI 04 (Dean, Ghemawat)



# MapReduce

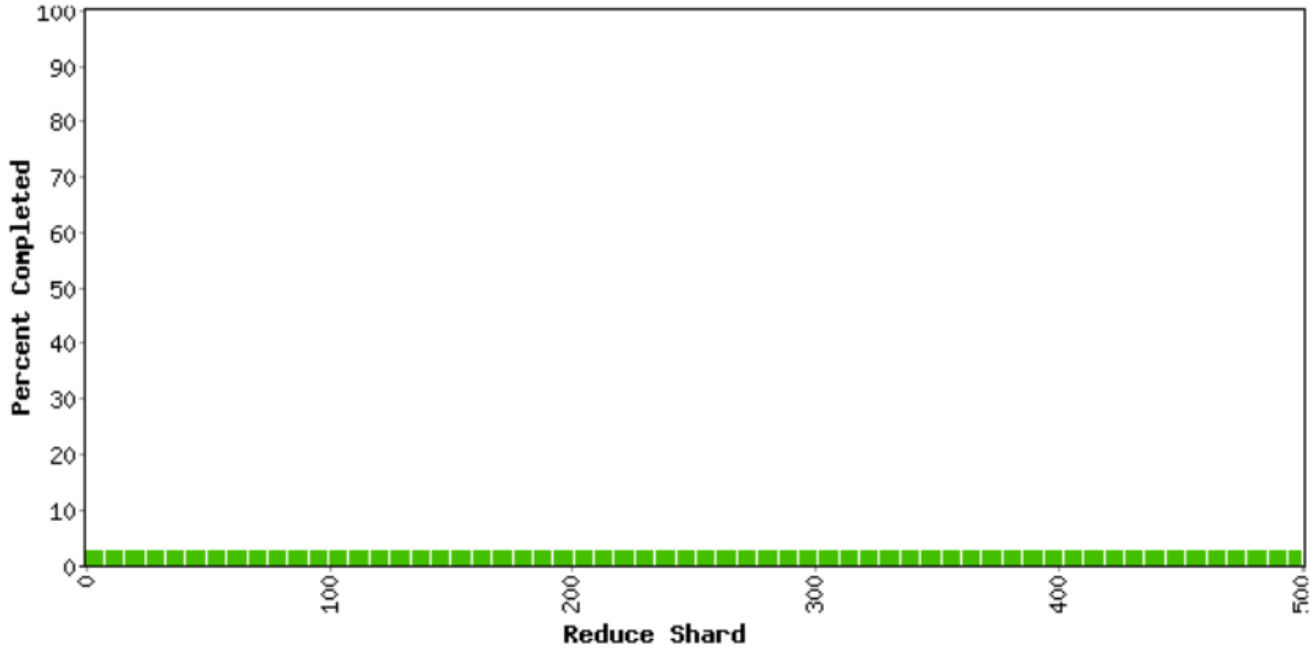
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 00 min 18 sec

323 workers; 0 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 0 | 323 | 878934.6 | 1314.4 | 717.0 |
| Shuffle | 500 | 0 | 323 | 717.0 | 0.0 | 0.0 |
| Reduce | 500 | 0 | 0 | 0.0 | 0.0 | 0.0 |




Counters

| Variable | Minute |
|---|---|
| Mapped (MB/s) | 72.5 |
| Shuffle (MB/s) | 0.0 |
| Output (MB/s) | 0.0 |
| doc-index-hits | 145825686 |
| docs-indexed | 506631 |
| dups-in-index-merge | 0 |
| mr-operator-calls | 508192 |
| mr-operator- | 506631 |

# MapReduce

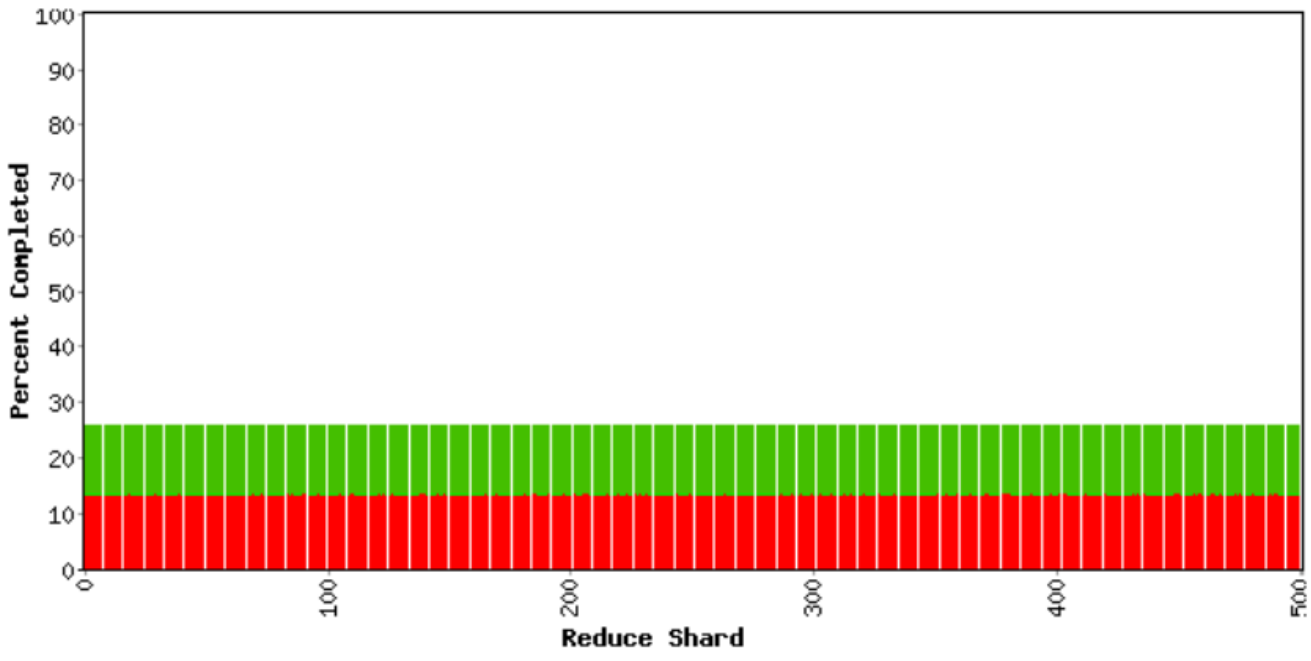
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 05 min 07 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 1857 | 1707 | 878934.6 | 191995.8 | 113936.6 |
| Shuffle | 500 | 0 | 500 | 113936.6 | 57113.7 | 57113.7 |
| Reduce | 500 | 0 | 0 | 57113.7 | 0.0 | 0.0 |




Counters

| Variable | Minute |
|---|---|
| Mapped (MB/s) | 699.1 |
| Shuffle (MB/s) | 349.5 |
| Output (MB/s) | 0.0 |
| doc-index-hits | 5004411944 |
| docs-indexed | 17290135 |
| dups-in-index-merge | 0 |
| mr-operator-calls | 17331371 |
| mr-operator-outputs | 17290135 |

# MapReduce

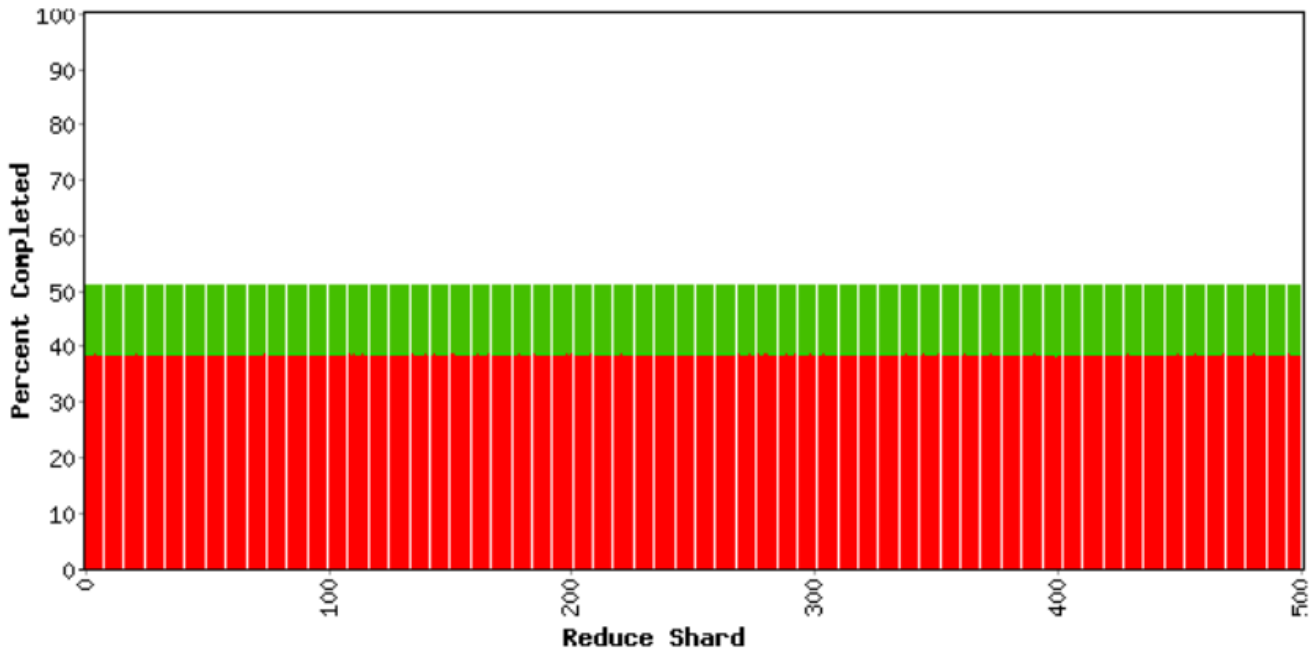
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 10 min 18 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 5354 | 1707 | 878934.6 | 406020.1 | 241058.2 |
| Shuffle | 500 | 0 | 500 | 241058.2 | 196362.5 | 196362.5 |
| Reduce | 500 | 0 | 0 | 196362.5 | 0.0 | 0.0 |




Counters

| Variable | Minute |
|---|---|
| Mapped (MB/s) | 704.4 |
| Shuffle (MB/s) | 371.9 |
| Output (MB/s) | 0.0 |
| doc-index-hits | 5000364228 |
| docs-indexed | 17300709 |
| dups-in-index-merge | 0 |
| mr-operator-calls | 17342493 |
| mr-operator-outputs | 17300709 |

# MapReduce

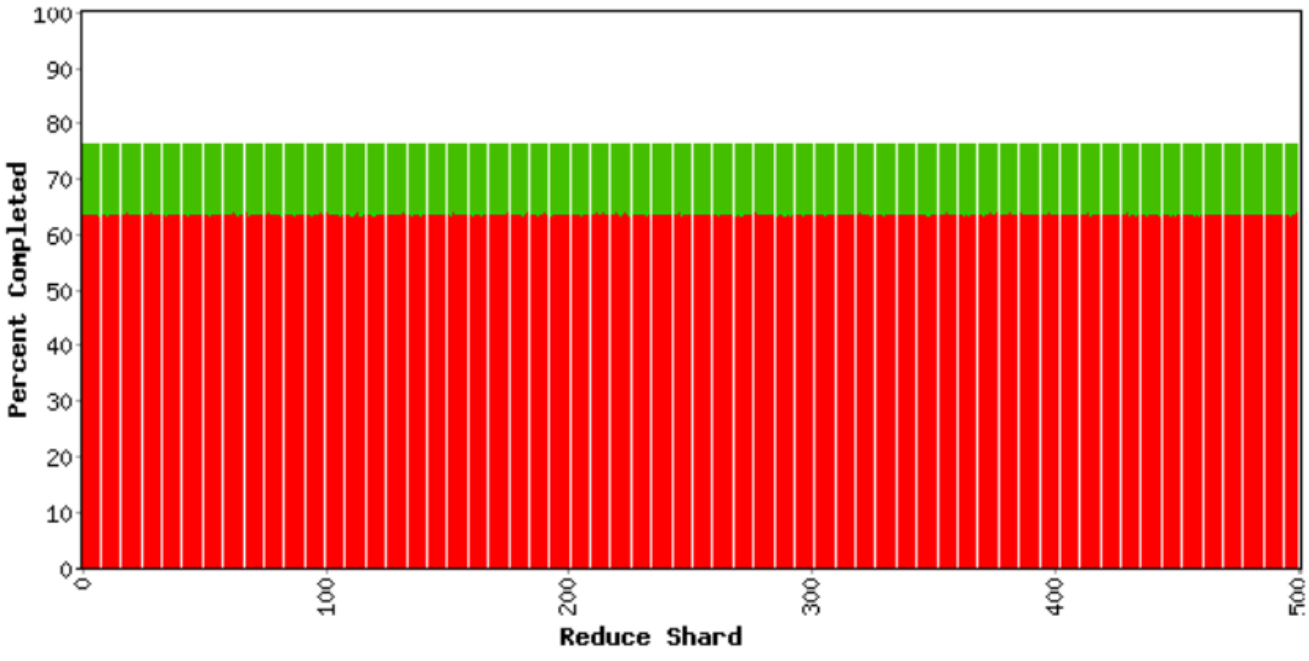
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 15 min 31 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 8841 | 1707 | 878934.6 | 621608.5 | 369459.8 |
| Shuffle | 500 | 0 | 500 | 369459.8 | 326986.8 | 326986.8 |
| Reduce | 500 | 0 | 0 | 326986.8 | 0.0 | 0.0 |




Counters

| Variable | Minute |
|---|---|
| Mapped (MB/s) | 706.5 |
| Shuffle (MB/s) | 419.2 |
| Output (MB/s) | 0.0 |
| doc-index-hits | 4982870667 |
| docs-indexed | 17229926 |
| dups-in-index-merge | 0 |
| mr-operator-calls | 17272056 |
| mr-operator-outputs | 17229926 |

# MapReduce

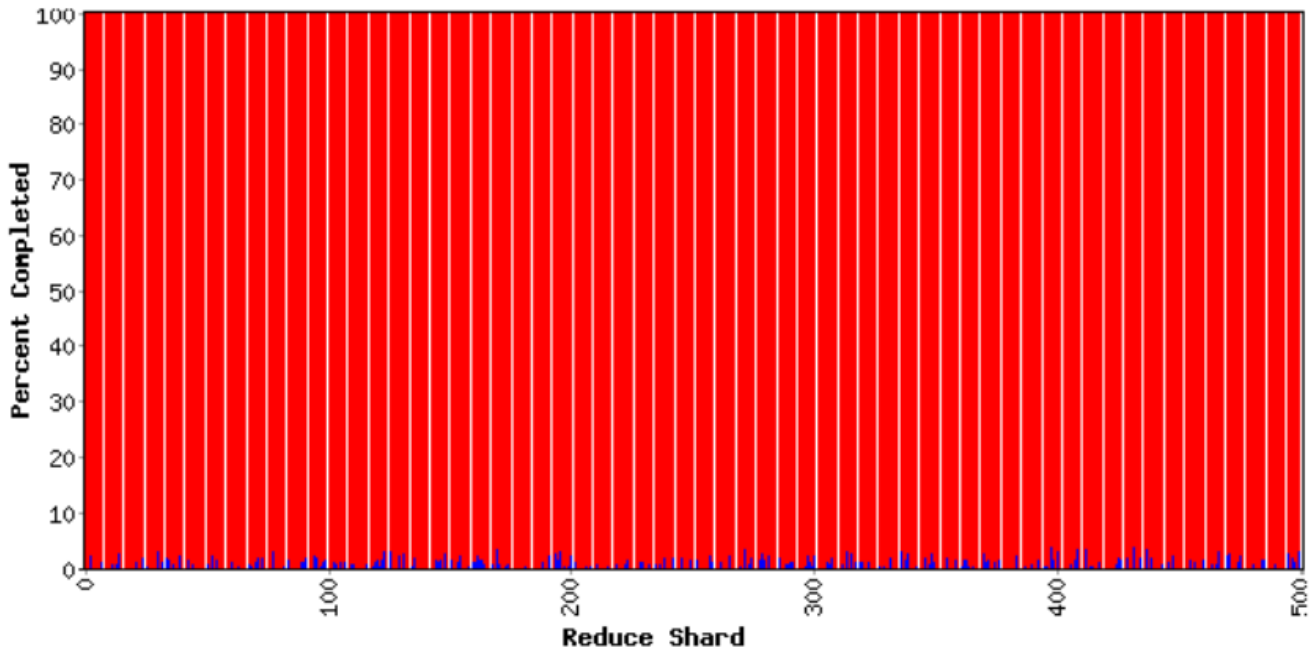
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 29 min 45 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 13853 | 0 | 878934.6 | 878934.6 | 523499.2 |
| Shuffle | 500 | 195 | 305 | 523499.2 | 523389.6 | 523389.6 |
| Reduce | 500 | 0 | 195 | 523389.6 | 2685.2 | 2742.6 |




Counters

| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.3 | |
| Shuffle (MB/s) | 0.5 | |
| Output (MB/s) | 45.7 | |
| doc-index-hits | 2313178 | 10 |
| docs-indexed | 7936 | |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 1954105 | |
| mr-merge-outputs | 1954105 | |

# MapReduce

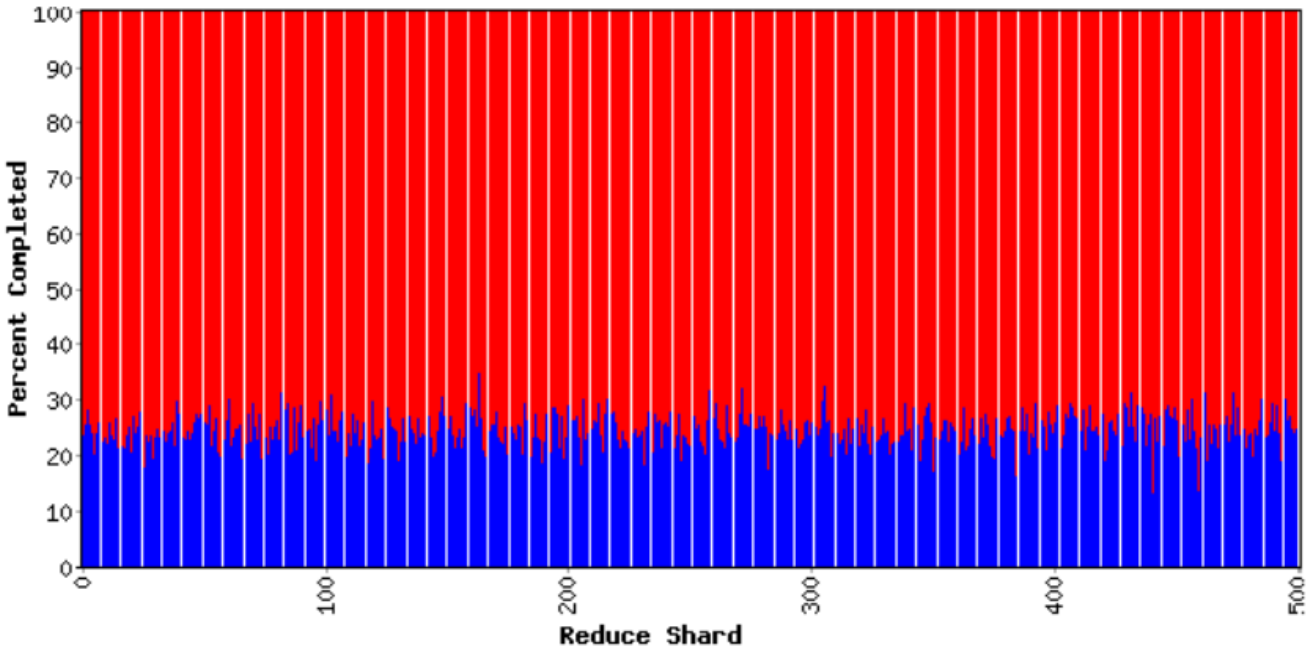
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 31 min 34 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 13853 | 0 | 878934.6 | 878934.6 | 523499.2 |
| Shuffle | 500 | 500 | 0 | 523499.2 | 523499.5 | 523499.5 |
| Reduce | 500 | 0 | 500 | 523499.5 | 133837.8 | 136929.6 |




Counters

| Variable | Minute |
|---|---|
| Mapped (MB/s) | 0.0 |
| Shuffle (MB/s) | 0.1 |
| Output (MB/s) | 1238.8 |
| doc-index-hits | 0 |
| docs-indexed | 0 |
| dups-in-index-merge | 0 |
| mr-merge-calls | 51738599 |
| mr-merge-outputs | 51738599 |

# MapReduce

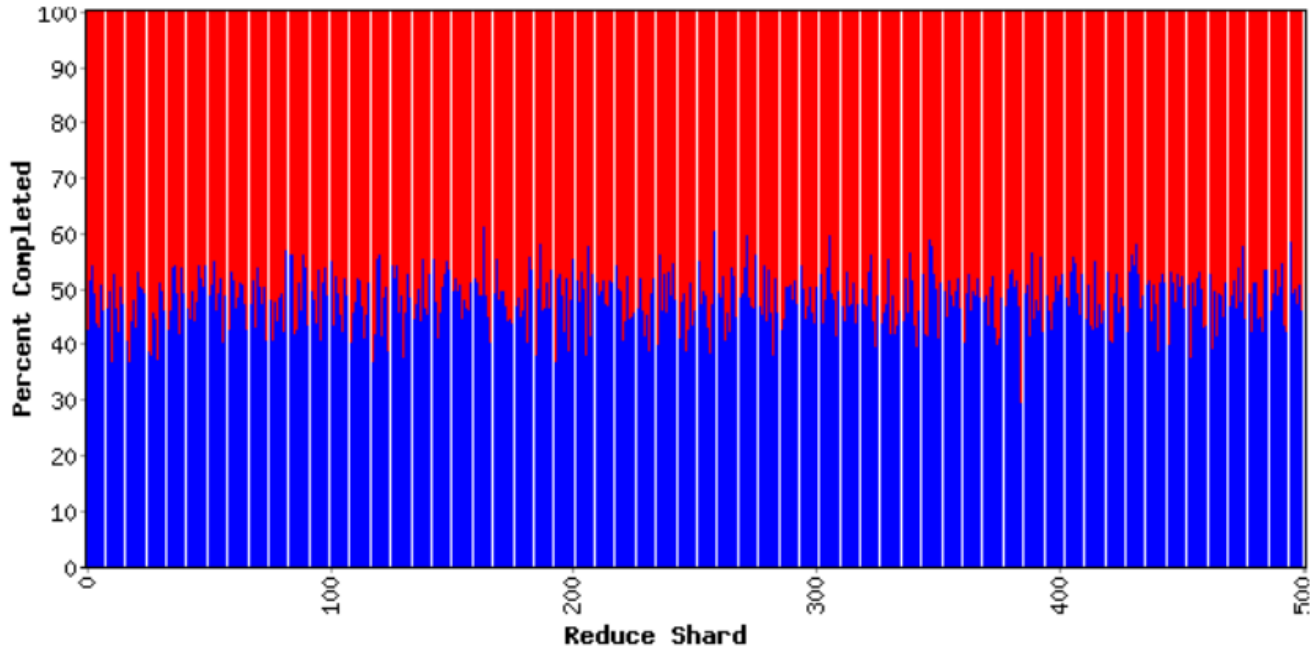
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 33 min 22 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 13853 | 0 | 878934.6 | 878934.6 | 523499.2 |
| Shuffle | 500 | 500 | 0 | 523499.2 | 523499.5 | 523499.5 |
| Reduce | 500 | 0 | 500 | 523499.5 | 263283.3 | 269351.2 |




Counters

| Variable | Minute |
|---|---|
| Mapped (MB/s) | 0.0 |
| Shuffle (MB/s) | 0.0 |
| Output (MB/s) | 1225.1 |
| doc-index-hits | 0 |
| docs-indexed | 0 |
| dups-in-index-merge | 0 |
| mr-merge-calls | 51842100 |
| mr-merge-outputs | 51842100 |

# MapReduce

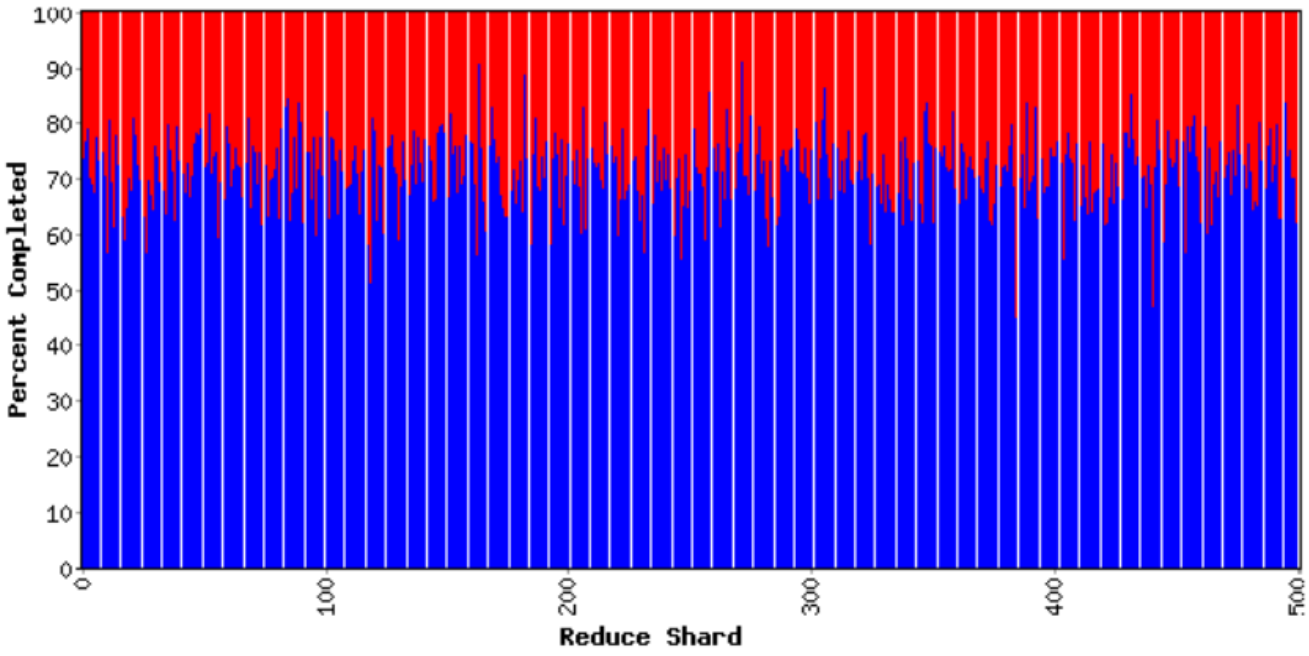
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 35 min 08 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 13853 | 0 | 878934.6 | 878934.6 | 523499.2 |
| Shuffle | 500 | 500 | 0 | 523499.2 | 523499.5 | 523499.5 |
| Reduce | 500 | 0 | 500 | 523499.5 | 390447.6 | 399457.2 |




Counters

| Variable | Minute |
|---|---|
| Mapped (MB/s) | 0.0 |
| Shuffle (MB/s) | 0.0 |
| Output (MB/s) | 1222.0 |
| doc-index-hits | 0 |
| docs-indexed | 0 |
| dups-in-index-merge | 0 |
| mr-merge-calls | 51640600 |
| mr-merge-outputs | 51640600 |

# MapReduce

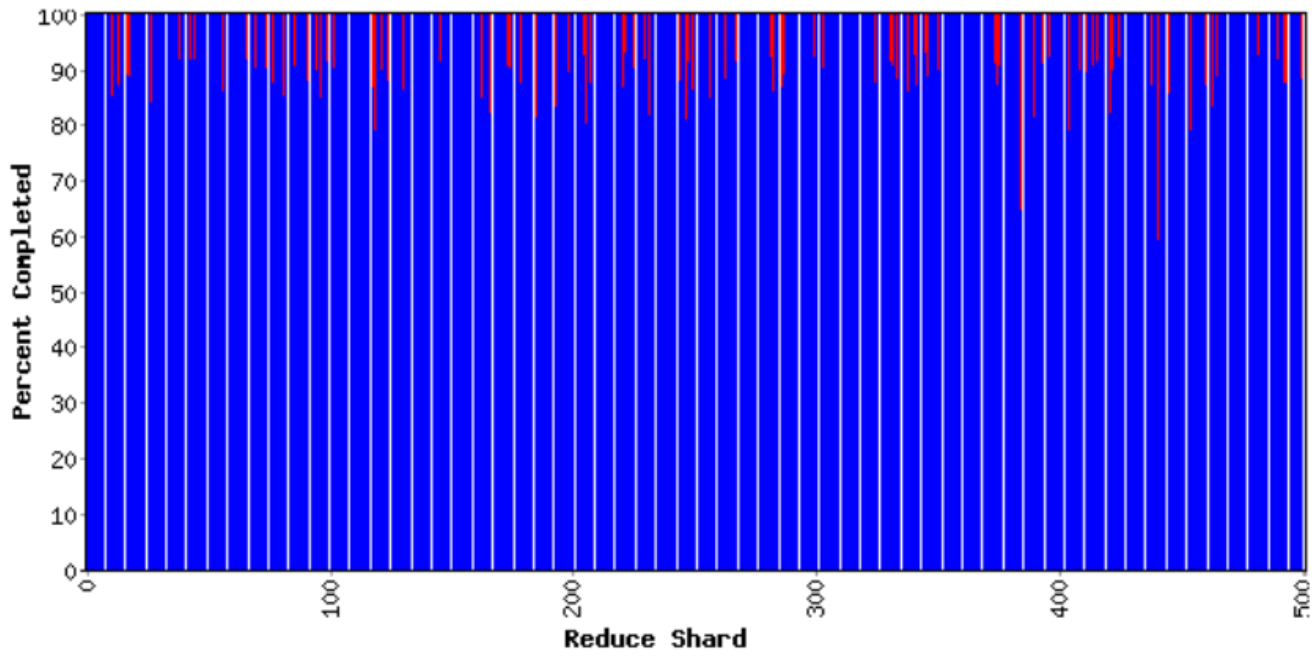
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 37 min 01 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 13853 | 0 | 878934.6 | 878934.6 | 523499.2 |
| Shuffle | 500 | 500 | 0 | 523499.2 | 520468.6 | 520468.6 |
| Reduce | 500 | 406 | 94 | 520468.6 | 512265.2 | 514373.3 |




Counters

| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.0 | |
| Shuffle (MB/s) | 0.0 | |
| Output (MB/s) | 849.5 | |
| doc-index-hits | 0 | 1( |
| docs-indexed | 0 | |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 35083350 | |
| mr-merge-outputs | 35083350 | |

# MapReduce

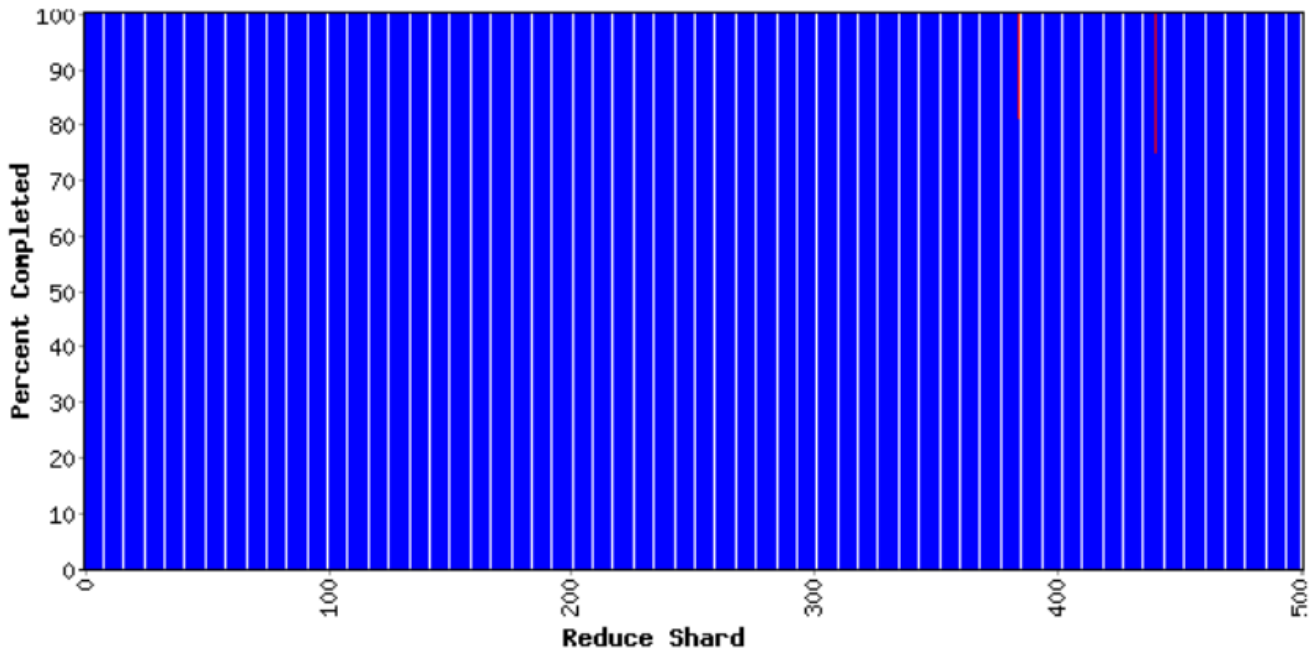
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 38 min 56 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 13853 | 0 | 878934.6 | 878934.6 | 523499.2 |
| Shuffle | 500 | 500 | 0 | 523499.2 | 519781.8 | 519781.8 |
| Reduce | 500 | 498 | 2 | 519781.8 | 519394.7 | 519440.7 |




Counters

| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.0 | |
| Shuffle (MB/s) | 0.0 | |
| Output (MB/s) | 9.4 | |
| doc-index-hits | 0 | 1056 |
| docs-indexed | 0 | 1 |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 394792 | 1 |
| mr-merge-outputs | 394792 | 1 |

# MapReduce

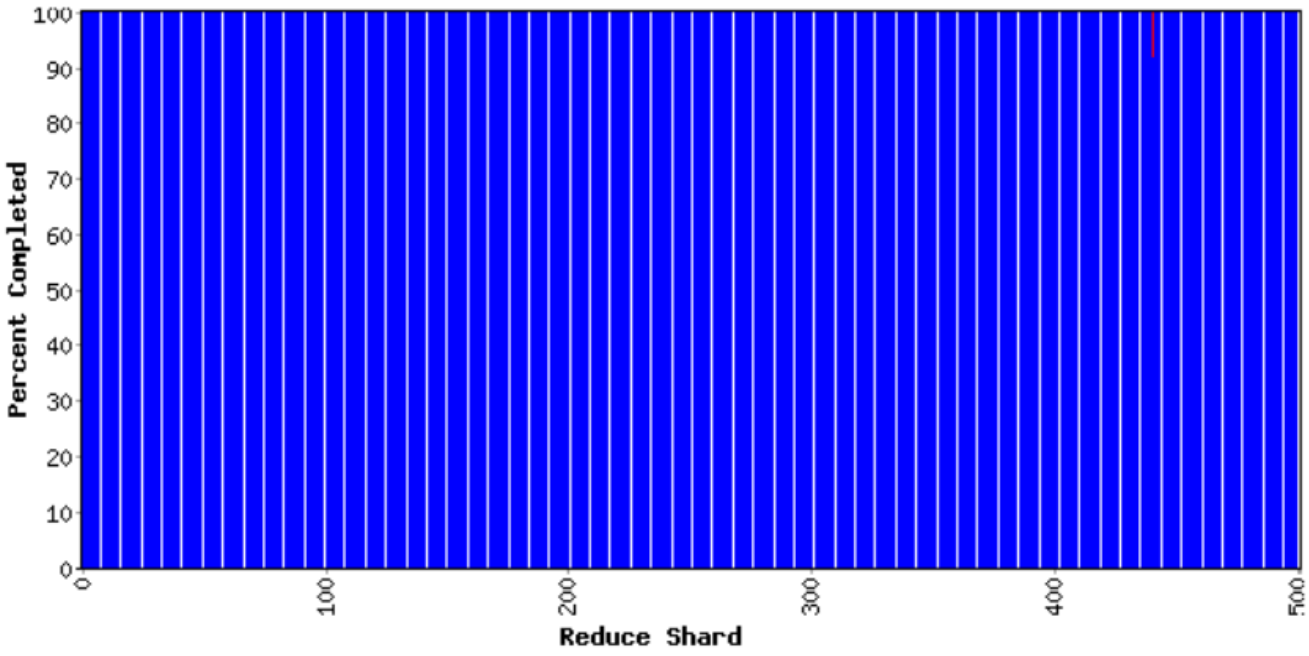
## OSDI 04 (Dean, Ghemawat)

### MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

Started: Fri Nov 7 09:51:07 2003 -- up 0 hr 40 min 43 sec

1707 workers; 1 deaths

| Type | Shards | Done | Active | Input(MB) | Done(MB) | Output(MB) |
|---|---|---|---|---|---|---|
| Map | 13853 | 13853 | 0 | 878934.6 | 878934.6 | 523499.2 |
| Shuffle | 500 | 500 | 0 | 523499.2 | 519774.3 | 519774.3 |
| Reduce | 500 | 499 | 1 | 519774.3 | 519735.2 | 519764.0 |




Counters

| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.0 | |
| Shuffle (MB/s) | 0.0 | |
| Output (MB/s) | 1.9 | |
| doc-index-hits | 0 | 105 |
| docs-indexed | 0 | |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 73442 | |
| mr-merge-outputs | 73442 | |

# Last Reducer

Typically Map phase linear on blocks. Reducers more variable.

No answer until the last one is done!
Some machines get slow/crash!

Solution: Automatically run back-up copies. Take first to complete.

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Some machines get slow/crash!

Solution: Automatically run back-up copies. Take first to complete.

Scheduled by *Master Node*
Organizes computation, but does not process data.
If this fails, all goes down.

# Example 1: Word Count

Given text corpus $\langle$ doc id, list of words $\rangle$, count how many of each word exists.

**Map:**

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Given text corpus $\langle$ doc id, list of words $\rangle$, count how many of each word exists.

**Map:**
For each word $w \rightarrow \langle w, 1 \rangle$

**Reduce:**

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$\{\langle w, c_1 \rangle, \langle w, c_2 \rangle, \langle w, c_3 \rangle, \ldots\} \rightarrow$

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$w =$ "the" is 7% of all words!
**Combine:** (before Map goes to Shuffle phase)
$\{\langle w, c_1 \rangle, \langle w, c_2 \rangle, \langle w, c_3 \rangle, \ldots\} \rightarrow \langle w, \sum_i c_i \rangle$

# Example 1: Word Count - Actual Code

```
package org.myorg;

import java.io.IOException;
import java.util.*;

import org.apache.hadoop.fs.Path;
import org.apache.hadoop.conf.*;
import org.apache.hadoop.io.*;
import org.apache.hadoop.mapreduce.*;
import org.apache.hadoop.mapreduce.lib.input.FileInputFormat;
import org.apache.hadoop.mapreduce.lib.input.TextInputFormat;
import org.apache.hadoop.mapreduce.lib.output.FileOutputFormat;
import org.apache.hadoop.mapreduce.lib.output.TextOutputFormat;
```

# Example 1: Word Count - Actual Code

```
public class WordCount {

 public static class Map extends Mapper<LongWritable, Text, Text, IntWritable> {
    private final static IntWritable one = new IntWritable(1);
    private Text word = new Text();

    public void map(LongWritable key, Text value, Context context) throws IOException,
InterruptedException {
        String line = value.toString();
        StringTokenizer tokenizer = new StringTokenizer(line);
        while (tokenizer.hasMoreTokens()) {
            word.set(tokenizer.nextToken());
            context.write(word, one);
        }
    }
 }
```

# Example 1: Word Count - Actual Code

```
public static class Reduce extends Reducer<Text, IntWritable, Text, IntWritable> {

   public void reduce(Text key, Iterator<IntWritable> values, Context context)
     throws IOException, InterruptedException {
       int sum = 0;
       while (values.hasNext()) {
           sum += values.next().get();
       }
       context.write(key, new IntWritable(sum));
   }
}
```

# Example 1: Word Count - Actual Code

```
public static void main(String[] args) throws Exception {
    Configuration conf = new Configuration();

        Job job = new Job(conf, "wordcount");

    job.setOutputKeyClass(Text.class);
    job.setOutputValueClass(IntWritable.class);

    job.setMapperClass(Map.class);
    job.setReducerClass(Reduce.class);

    job.setInputFormatClass(TextInputFormat.class);
    job.setOutputFormatClass(TextOutputFormat.class);

    FileInputFormat.addInputPath(job, new Path(args[0]));
    FileOutputFormat.setOutputPath(job, new Path(args[1]));

    job.waitForCompletion(true);
}

}
```

job.setCombinerClass(Reduce.class);

# Example 2: Inverted Index

Given all of Wikipedia (all webpages), for each word, list all pages it is on.

**Map:**

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**Map:**
For page $p$, each word $w \rightarrow \langle w, p \rangle$

**Reduce:**

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**Reduce:**
$\{\langle w, p_1 \rangle, \langle w, p_2 \rangle, \langle w, p_3 \rangle, \ldots\} \rightarrow$

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**Map:**
For page $p$, each word $w \rightarrow \langle w, p \rangle$

**Reduce:**
$\{\langle w, p_1 \rangle, \langle w, p_2 \rangle, \langle w, p_3 \rangle, \ldots\} \rightarrow \langle w, \cup_i p_i \rangle$

# Example 2: Inverted Index

Given all of Wikipedia (all webpages), for each word, list all pages it is on.

**Map:**
For page $p$, each word $w \rightarrow \langle w, p \rangle$

**Combine:**
$\{\langle w, p_1 \rangle, \langle w, p_2 \rangle, \langle w, p_3 \rangle, \ldots\} \rightarrow \langle w, \cup_i p_i \rangle$

**Reduce:**
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# Hadoop

Open source version of MapReduce (and related, e.g. HDFS)

- Began 2005 (Cutting + Cafarella) supported by Yahoo!
- Stable enough for large scale around 2008
- Source code released 2009

Java (MapReduce in C++)

Led to *widespread* adoption in industry and academia!

# Rounds

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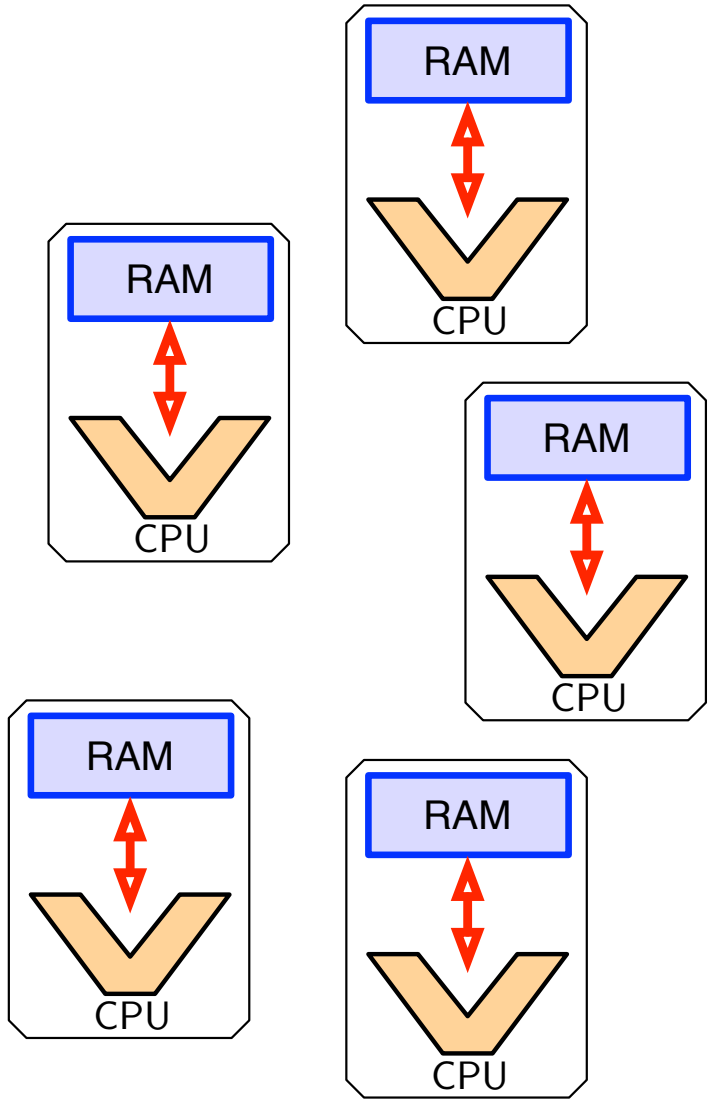
MRC Model (Karloff, Suri, Vassilvitskii; SODA 2010).
Stresses Rounds.

# Bulk Synchronous Parallel

Les Valiant [1989] BSP
Creates "barriers" in parallel algorithm.

1. Each processor computes on data
2. Processors send/receive data
3. Barrier : All processors wait for communication to end globally

Allows for easy synchronization. Easier to analyze since handles many messy synchronization details if this is emulated.



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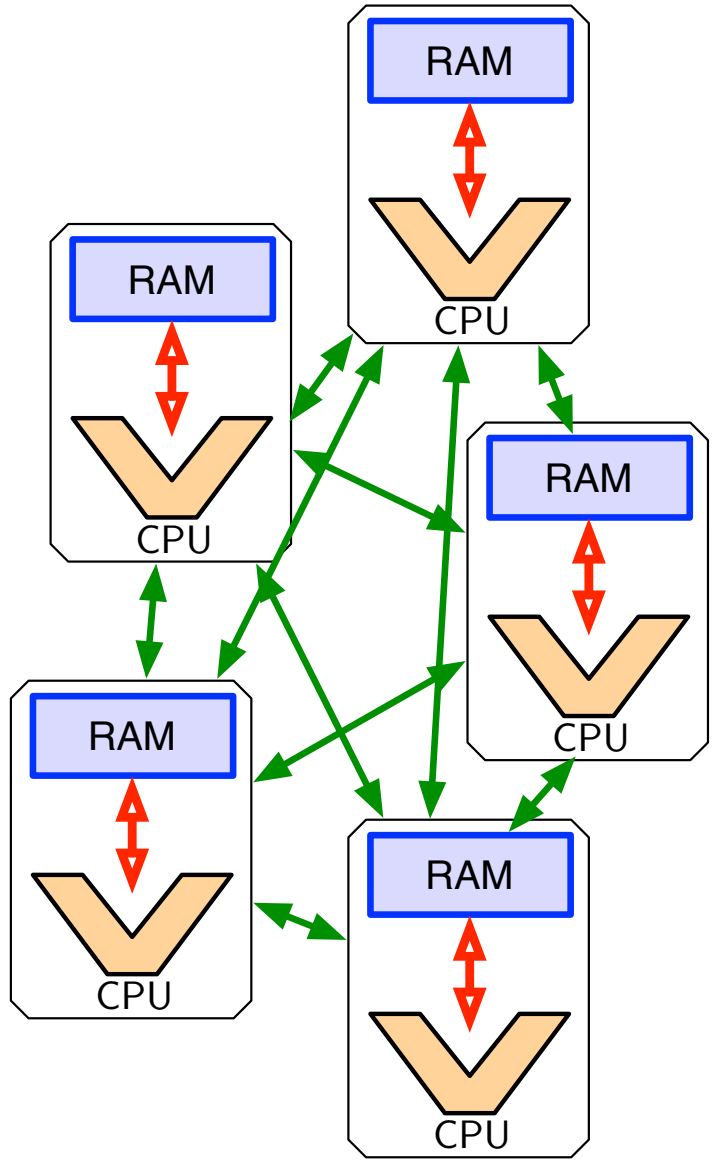

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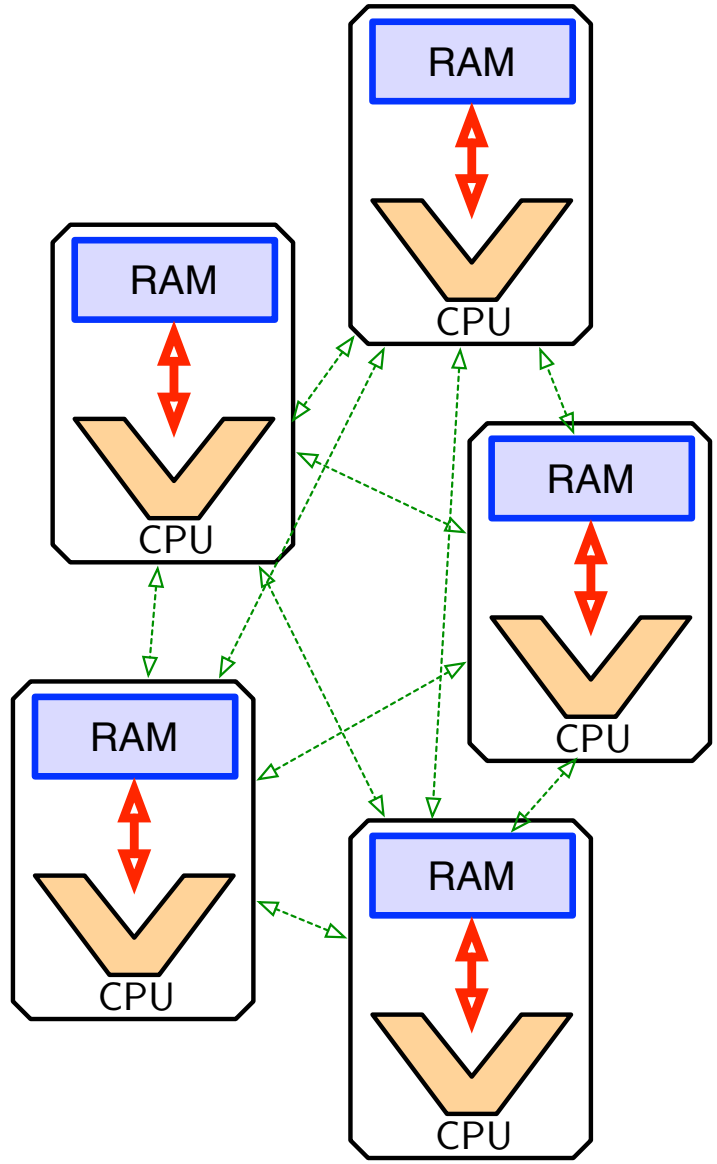


Reduction from MR (Goodrich, Sitchinava, Zhang; ISAAC 2011)

# Replication Rate

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List pair $(r, s) \in R \times S$ if $f(r, s) = 1$, for some function $f$.

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(Afrati, Das Sarma, Salihoglu, Ullman 2013),
(Beame, Koutris, Suciu 2013)

# Sawzall / Dremel / Tenzing

Google solution to *many to few*:

- Compute statistics on massive distributed data.
- Separates local computation from aggregation.
- Better with Iteration

| | Sawzall | Tenzing | Dremel |
|---|---|---|---|
| Latency | high | med | low |
| Scalability | high | high | med |
| SQL | none | high | med |
| Power | high | med | low |

# Berkeley Spark: Processing in memory

Zaharia, Chowdhury, Das, Ma, McCauley, Franklin, Shenker, Stoica (HotCloud 2010, NSDI 2012)

- Keeps relevant information in memory.
- Much faster on iterative algorithms (machine learning, SQL queries)
- Requires careful work to retain resiliency

Key idea: *RDDs: Resilient Distributed Data*. Can be stored in memory without replication, rebuilt from lineage if lost.