# MapReduce: Simplified Data Processing on Large Clusters

PA154 Language Modeling (7.3)

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**Source:** Jeff Dean, Sanjay Ghemawat
Google, Inc.
December, 2004
https://research.google/pubs/pub62/

# Motivation: Large Scale Data Processing

Many tasks: Process lots of data to produce other data
Want to use hundreds or thousands of CPUs

- ... but this needs to be easy

MapReduce provides:

- Automatic parallelization and distribution
- Fault-tolerance
- I/O scheduling
- Status and monitoring

# Programming model

Input & Output: each a set of key/value pairs Programmer specifies two functions:

```
map (in_key, in_value) -> list(out_key, intermediate_value)
```

- Processes input key/value pair
- Produces set of intermediate pairs

```
reduce (out_key, list(intermediate_value)) -> list(out_value)
```

- Combines all intermediate values for a particular key
- Produces a set of merged output values (usually just one)

Inspired by similar primitives in LISP and other languages

# Example: Count word occurrences

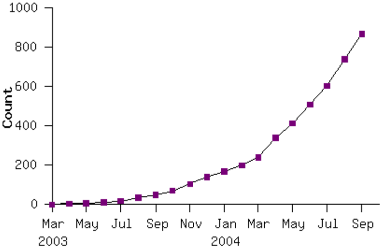
```
map(String input_key, String input_value):
  // input_key: document name
  // input_value: document contents
  for each word w in input_value:
    EmitIntermediate(w, "1");

reduce(String output_key, Iterator intermediate_values):
  // output_key: a word
  // output_values: a list of counts
  int result = 0;
  for each v in intermediate_values:
    result += ParseInt(v);
  Emit(AsString(result));
```

Pseudocode: See appendix in paper for real code

# Model is Widely Applicable

MapReduce Programs In Google Source Tree




Example uses:

| | | |
|---|---|---|
| distributed grep | distributed sort | web link-graph reversal |
| term-vector per host | web access log stats | inverted index construction |
| document clustering | machine learning | statistical machine translation |
| ... | ... | ... |

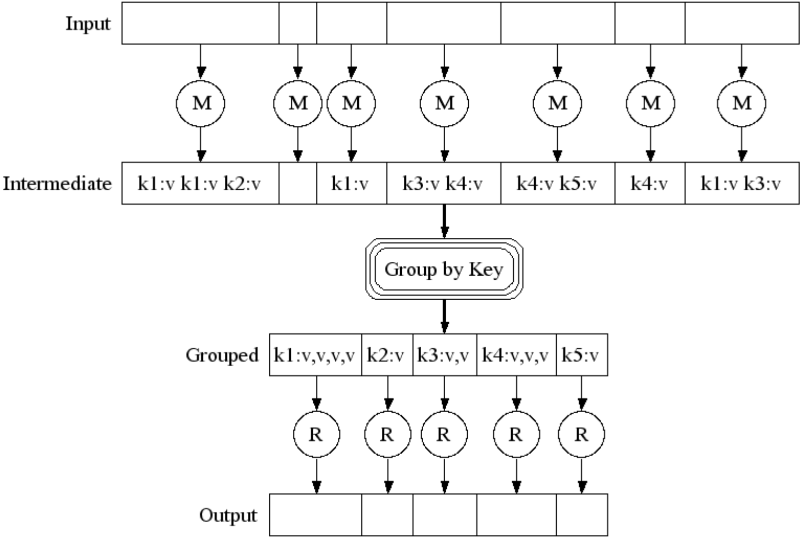
# Implementation Overview

Typical cluster:

- 100s/1000s of 2-CPU x86 machines, 2-4 GB of memory
- Limited bisection bandwidth
- Storage is on local IDE disks
- GFS: distributed file system manages data (SOSP'03)
- Job scheduling system: jobs made up of tasks, scheduler assigns tasks to machines

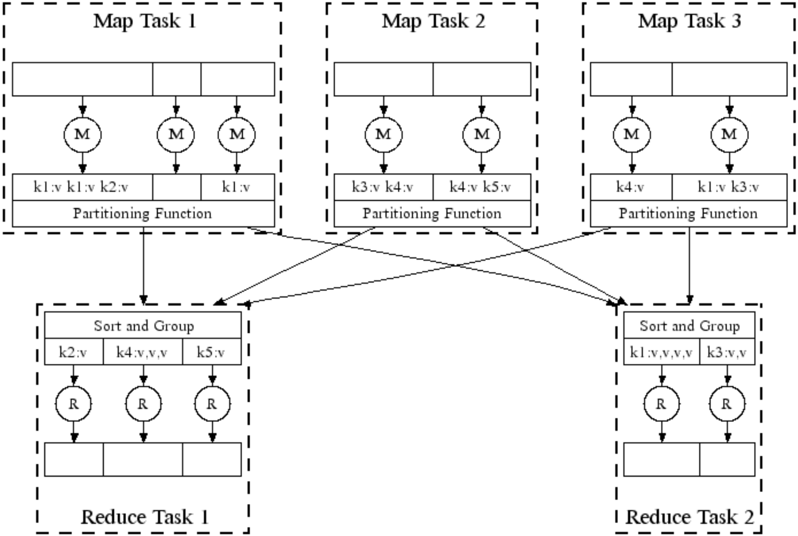
Implementation is a C++ library linked into user programs

# Execution



Input
M
M
M
M
M
M
M
Intermediate
k1:v k1:v k2:v
k1:v
k3:v k4:v
k4:v k5:v
k4:v
k1:v k3:v
Group by Key
Grouped
k1:v,v,v,v
k2:v
k3:v,v
k4:v,v,v
k5:v
R
R
R
R
R
Output

# Parallel Execution

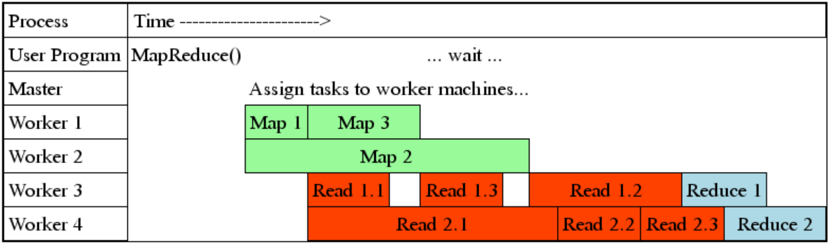


# Task Granularity And Pipelining

Fine granularity tasks: many more map tasks than machines

- Minimizes time for fault recovery
- Can pipeline shuffling with map execution
- Better dynamic load balancing

Often use 200,000 map/5000 reduce tasks/ 2000 machines

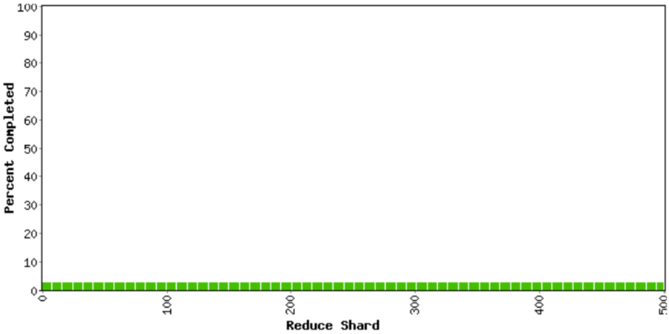


# MapReduce status: MR_Indexer-beta6-large-2003_10_28_00_03

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

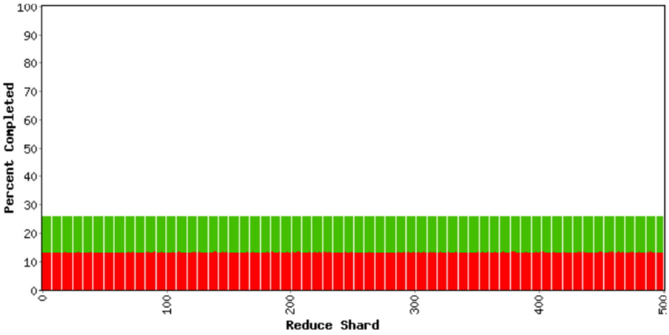
| Variable | Minute |
|---|---|
| Mapped (MB/s) | 72.5 |
| Shuffle (MB/s) | 0.0 |
| Output (MB/s) | 0.0 |
| doc-index-hits | 145825686 |
| docs-indexed | 506631 |
| dups-in-index-merge | 0 |
| mr-operator-calls | 508192 |
| mr-operator-outputs | 506631 |

# 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

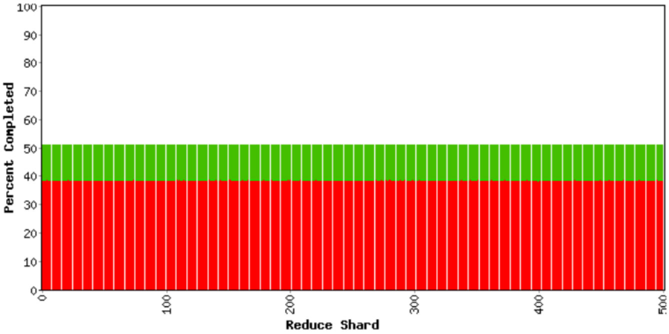
| Variable | Minute |
|---|---|
| Mapped (MB/s) | 699.1 |
| Shuffle (MB/s) | 349.5 |
| Output (MB/s) | 0.0 |
| doc-index-hits | 5004411944 |
| docs-indexed | 17290135 |
| dups-in-index-merge | 0 |
| mr-operator-calls | 17331371 |
| mr-operator-outputs | 17290135 |

# MapReduce 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 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

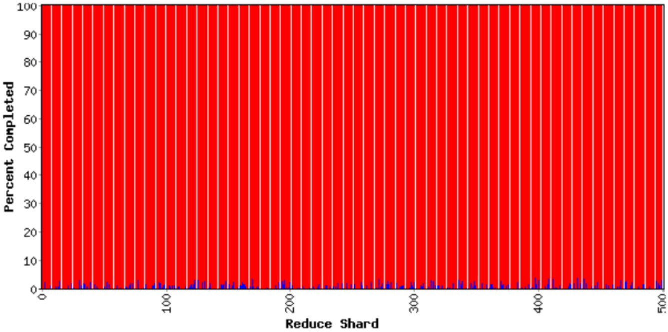
| Variable | Minute |
|---|---|
| Mapped (MB/s) | 706.5 |
| Shuffle (MB/s) | 419.2 |
| Output (MB/s) | 0.0 |
| doc-index-hits | 4982870667 |
| docs-indexed | 17229926 |
| dups-in-index-merge | 0 |
| mr-operator-calls | 17272056 |
| mr-operator-outputs | 17229926 |

# MapReduce 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

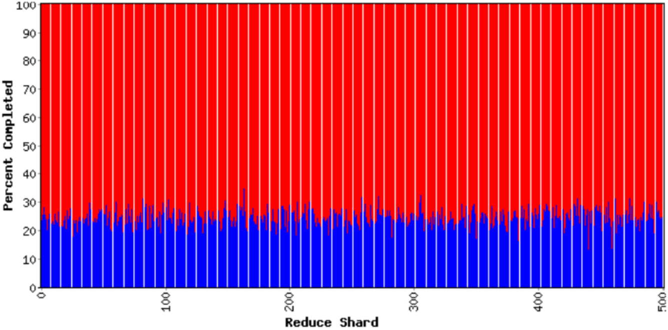
| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.3 | |
| Shuffle (MB/s) | 0.5 | |
| Output (MB/s) | 45.7 | |
| doc-index-hits | 2313178 | 105 |
| docs-indexed | 7936 | |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 1954105 | |
| mr-merge-outputs | 1954105 | |

# 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

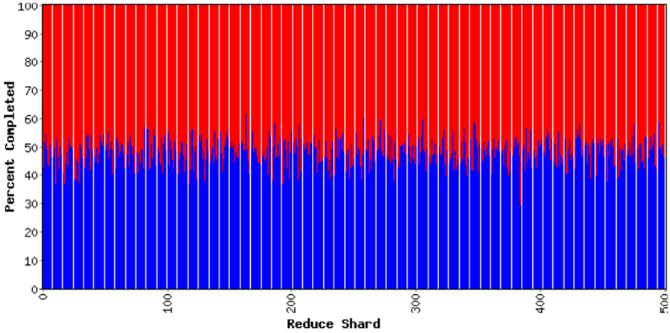
| Variable | Minute |
|---|---|
| Mapped (MB/s) | 0.0 |
| Shuffle (MB/s) | 0.1 |
| Output (MB/s) | 1238.8 |
| doc-index-hits | 0 |
| docs-indexed | 0 |
| dups-in-index-merge | 0 |
| mr-merge-calls | 51738599 |
| mr-merge-outputs | 51738599 |

# MapReduce 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

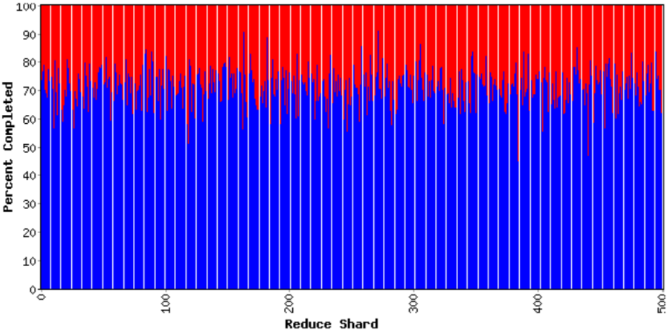
| Variable | Minute |
|---|---|
| Mapped (MB/s) | 0.0 |
| Shuffle (MB/s) | 0.0 |
| Output (MB/s) | 1225.1 |
| doc-index-hits | 0 |
| docs-indexed | 0 |
| dups-in-index-merge | 0 |
| mr-merge-calls | 51842100 |
| mr-merge-outputs | 51842100 |

# MapReduce 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

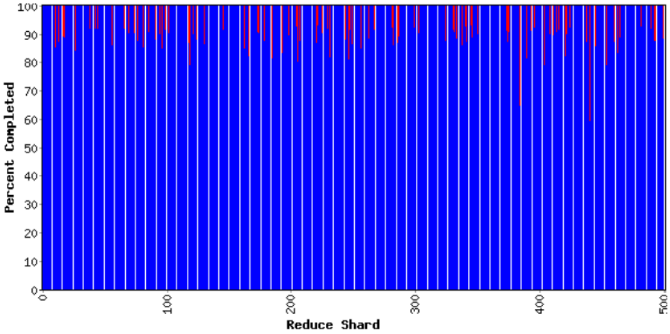
| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.0 | |
| Shuffle (MB/s) | 0.0 | |
| Output (MB/s) | 1222.0 | |
| doc-index-hits | 0 | 1( |
| docs-indexed | 0 | |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 51640600 | |
| mr-merge-outputs | 51640600 | |

# 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

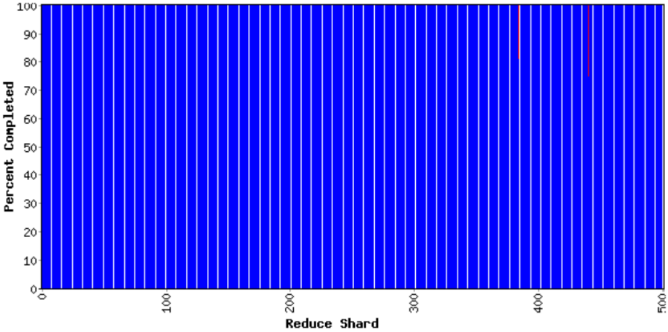
| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.0 | |
| Shuffle (MB/s) | 0.0 | |
| Output (MB/s) | 849.5 | |
| doc-index-hits | 0 | 10 |
| docs-indexed | 0 | |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 35083350 | |
| mr-merge-outputs | 35083350 | |

# 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

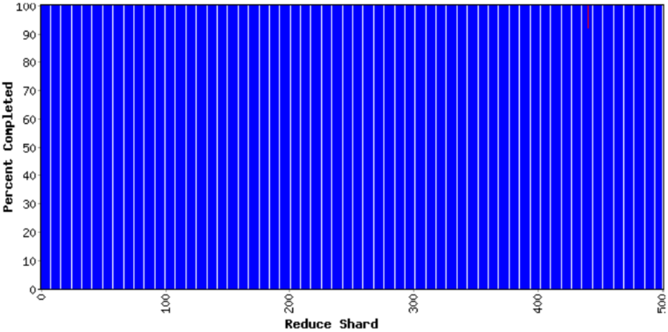
| Variable | Minute | |
|---|---|---|
| Mapped (MB/s) | 0.0 | |
| Shuffle (MB/s) | 0.0 | |
| Output (MB/s) | 9.4 | |
| doc-index-hits | 0 | 1056 |
| docs-indexed | 0 | |
| dups-in-index-merge | 0 | |
| mr-merge-calls | 394792 | |
| mr-merge-outputs | 394792 | |

# 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 | |

# Fault tolerance: Handled via re-execution

- On worker failure:
  - Detect failure via periodic heartbeats
  - Re-execute completed and in-progress map tasks
  - Re-execute in progress reduce tasks
  - Task completion committed through master
- Master failure:
  - Could handle, but don't yet (master failure unlikely)

Robust: lost 1600 of 1800 machines once, but finished fine

Semantics in presence of failures: see paper

# Refinement: Redundant Execution

Slow workers significantly lengthen completion time

- Other jobs consuming resources on machine
- Bad disks with soft errors transfer data very slowly
- Weird things: processor caches disabled (!!)

Solution: Near end of phase, spawn backup copies of tasks

- Whichever one finishes first ”wins”

Effect: Dramatically shortens job completion time

# Refinement: Locality Optimization

Master scheduling policy:

- Asks GFS for locations of replicas of input file blocks
- Map tasks typically split into 64MB (== GFS block size)
- Map tasks scheduled so GFS input block replica are on same machine or same rack

Effect: Thousands of machines read input at local disk speed

- Without this, rack switches limit read rate

# Refinement: Skipping Bad Records

Map/Reduce functions sometimes fail for particular inputs

- Best solution is to debug & fix, but not always possible
- On seg fault:
  - Send UDP packet to master from signal handler
  - Include sequence number of record being processed
- If master sees two failures for same record:
  - Next worker is told to skip the record

Effect: Can work around bugs in third-party libraries

# Other Refinements (see paper)

- Sorting guarantees within each reduce partition
- Compression of intermediate data
- Combiner: useful for saving network bandwidth
- Local execution for debugging/testing
- User-defined counters

# Performance

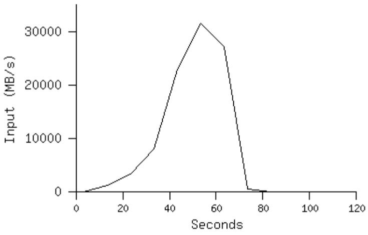
Tests run on cluster of 1800 machines:

- 4 GB of memory
- Dual-processor 2 GHz Xeons with Hyperthreading
- Dual 160 GB IDE disks
- Gigabit Ethernet per machine
- Bisection bandwidth approximately 100 Gbps

Two benchmarks:

| | |
|---|---|
| MR_Grep | Scan $10^{10}$ 100-byte records to extract records matching a rare pattern (92K matching records) |
| MR_Sort | Sort $10^{10}$ 100-byte records (modeled after TeraSort benchmark) |

# MR_Grep



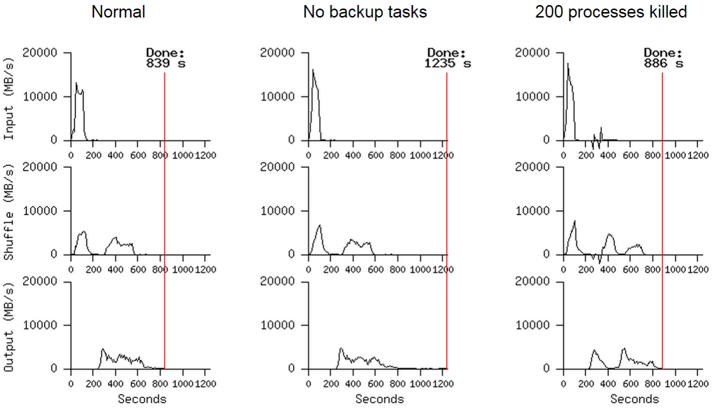

Locality optimization helps:

- 1800 machines read 1 TB of data at peak of $\approx$ 31 GB/s
- Without this, rack switches would limit to 10 GB/s

Startup overhead is significant for short jobs

# MR_Sort

- Backup tasks reduce job completion time significantly
- System deals well with failures



# Experience: Rewrite of Production Indexing System

Rewrote Google's production indexing system using MapReduce

- Set of ~~10~~, ~~14~~, ~~17~~, ~~21~~, 24 MapReduce operations
- New code is simpler, easier to understand
- MapReduce takes care of failures, slow machines
- Easy to make indexing faster by adding more machines

# Usage: MapReduce jobs run in August 2004

| | | |
|---|---|---|
| Number of jobs | 29,423 | |
| Average job completion time | 634 | secs |
| Machine days used | 79,186 | days |
| | | |
| Input data read | 3,288 | TB |
| Intermediate data produced | 758 | TB |
| Output data written | 193 | TB |
| | | |
| Average worker machines per job | 157 | |
| Average worker deaths per job | 1.2 | |
| Average map tasks per job | 3,351 | |
| Average reduce tasks per job | 55 | |
| | | |
| Unique map implementations | 395 | |
| Unique reduce implementations | 269 | |
| Unique map/reduce combinations | 426 | |

# Related Work

- Programming model inspired by functional language primitives
- Partitioning/shuffling similar to many large-scale sorting systems
  - NOW-Sort ['97]
- Re-execution for fault tolerance
  - BAD-FS ['04] and TACC ['97]
- Locality optimization has parallels with Active Disks/Diamond work
  - Active Disks ['01], Diamond ['04]
- Backup tasks similar to Eager Scheduling in Charlotte system
  - Charlotte ['96]
- Dynamic load balancing solves similar problem as River's distributed queues
  - River ['99]

# Conclusions

- MapReduce has proven to be a useful abstraction
- Greatly simplifies large-scale computations at Google
- Fun to use: focus on problem, let library deal w/ messy details

Thanks to Josh Levenberg, who has made many significant improvements and to everyone else at Google who has used and helped to improve MapReduce.