Joint Scheduling of Overlapping Phases in the MapReduce Framework

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Road Map

1. Introduction
2. Model and Formulation
3. General Greedy Solutions
4. Experiment
5. Conclusion

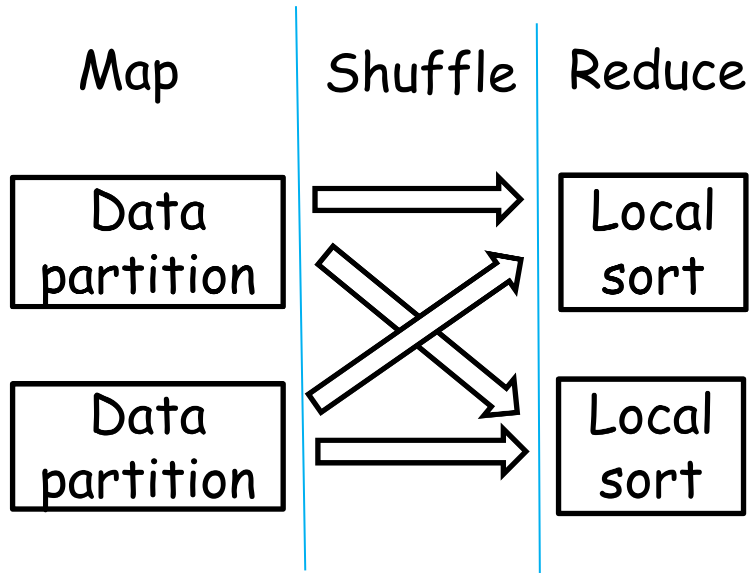
1. Introduction

Map-Shuffle-Reduce

- Map and Reduce: CPU-intensive
- Shuffle: I/O-intensive

TeraSort

- Map: sample & partition data
- Shuffle: partitioned data
- Reduce: locally sort data



Map-Shuffle-Reduce

- Multiple jobs
  - TeraSort, WordCount, etc.
- Reduce is not significant (Zaharia, OSDI 2008)
  - 7% of jobs are reduce-heavy

Centralized scheduler

Determines a sequential order for jobs on the map and shuffle pipelines

Job Classification

Dependency relationship

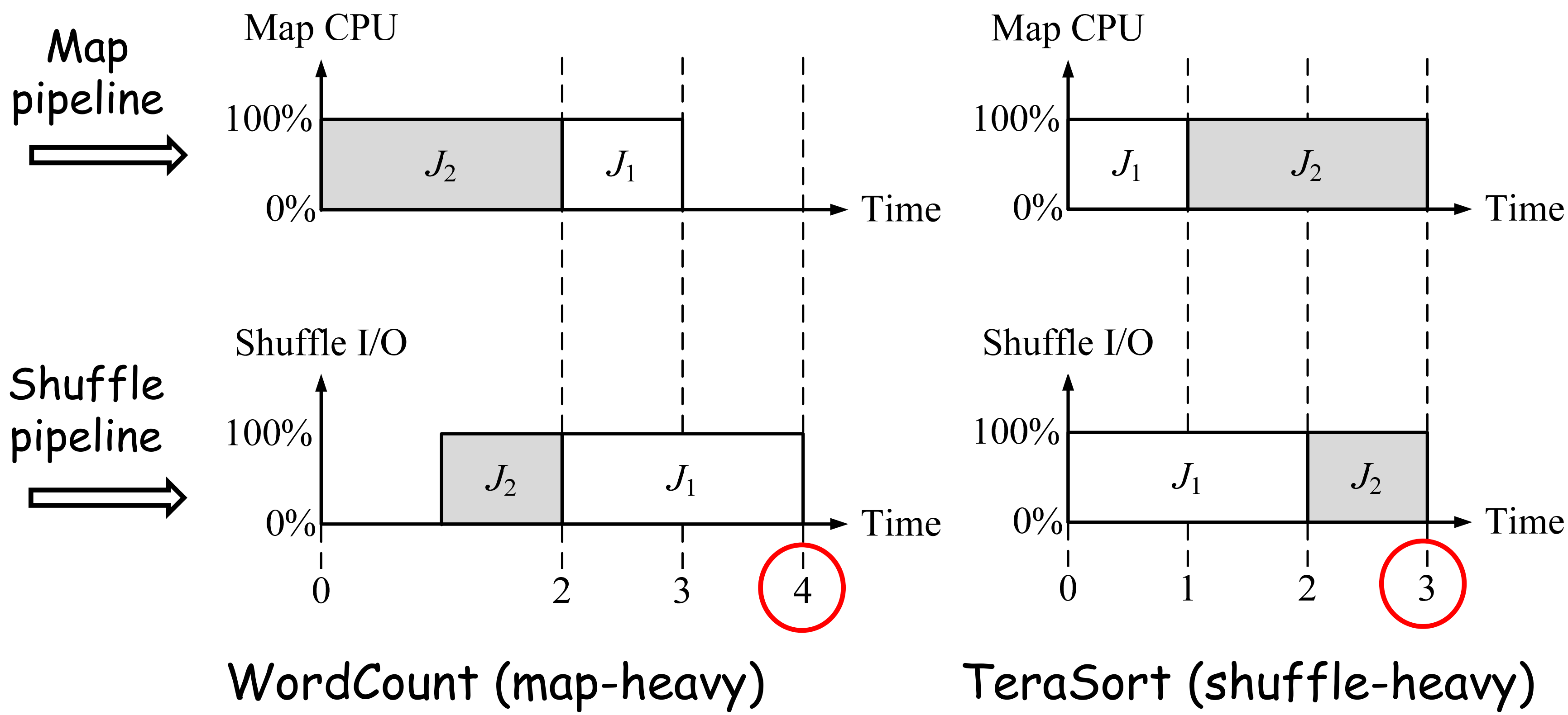
- Map emits data at a certain rate
- Shuffle waits for the map data

Job classification

Map-heavy:	map > shuffle	$(m > s)$
Balanced:	map = shuffle	$(m = s)$
Shuffle-heavy:	map < shuffle	$(m < s)$

Execution Order

Impact of overlapping map and shuffle

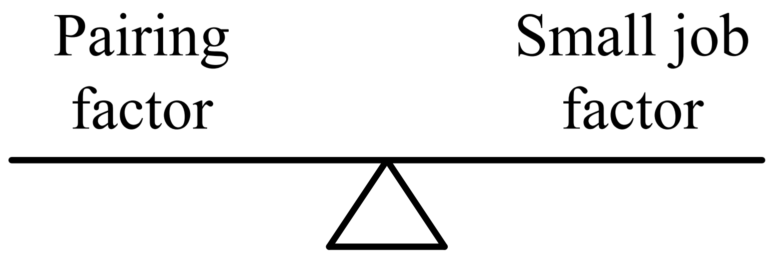


2. Model and Formulation

Schedule objective:

Minimize the average job completion time for all jobs;
J_i includes the wait time before the job starts.

Schedule is NP-hard



Offline scenarios

All jobs arrive at the beginning (and wait for schedule)

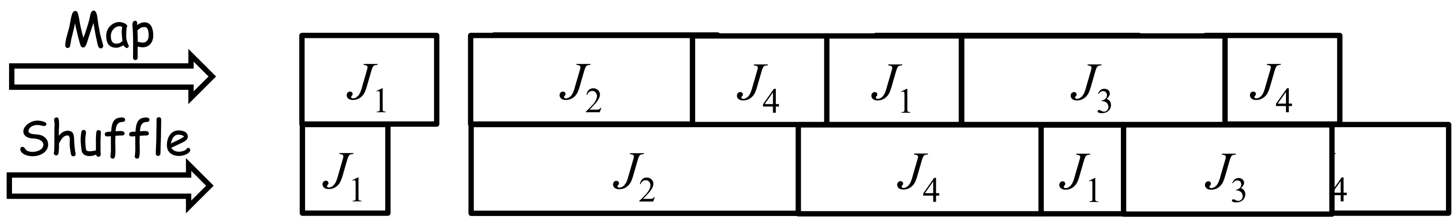
Related Work: Flow Shop

Minimize last job completion time

l-phase flow shop is solvable when l=2

- G_m: map-heavy jobs sorted in increasing order of map load
- G_s: shuffle-heavy jobs sorted in decreasing order of shuffle load

Optimal schedule: G_s followed by G_m



S. M. Johnson, Optimal two-and three-stage production schedules with setup times included, *Naval Research Logistics Quarterly*, 1954.

Related Work: Strong Pair

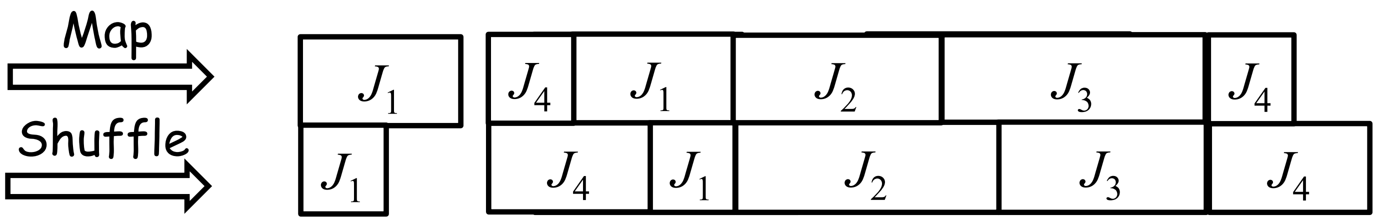
Minimize average job completion time

Strong pair

- J_1 and J_2 are a strong pair if $m_1 = s_2$ and $s_1 = m_2$

Optimal schedule: jobs are strong pairs

Pair jobs and rank pairs by total workloads



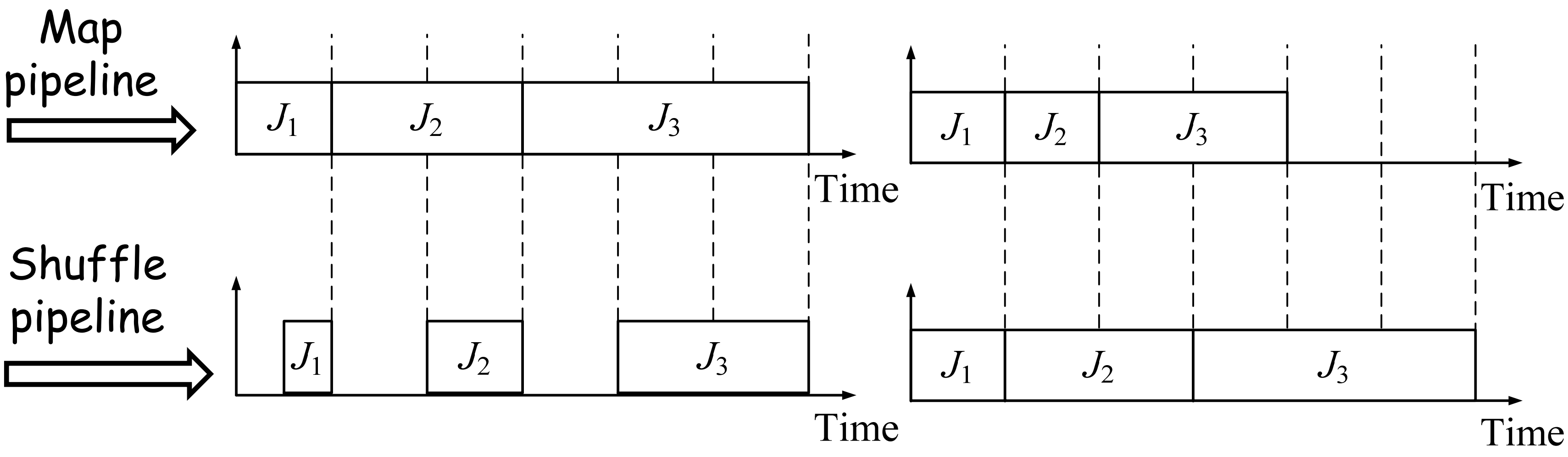
H. Zheng, Z. Wan, and J. Wu, Optimizing MapReduce framework through joint scheduling of overlapping phases, *Proc. of IEEE ICCCN*, 2016.

First Special Case

When all jobs are map-heavy, balanced, or shuffle-heavy

Optimal schedule:

- Sort jobs ascendingly by dominant workload max{m, s}
- Execute smaller jobs earlier



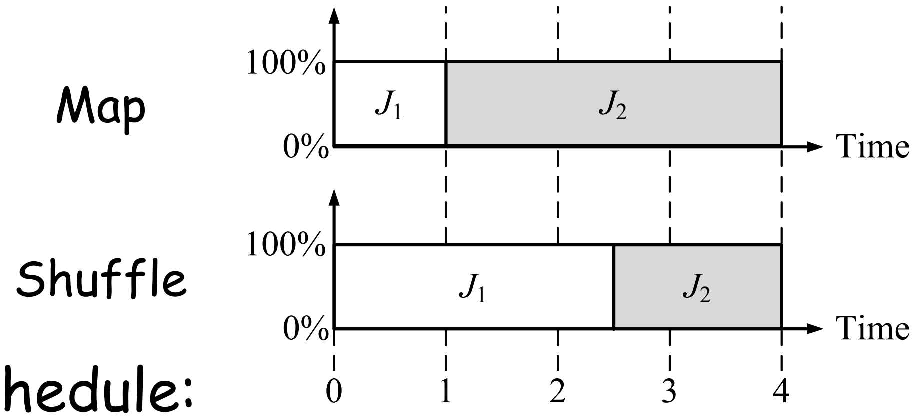
Finishing times J_1, J_2, J_3: 1, 3, 6 vs. J_3, J_2, J_1: 3, 5, 6

Second Special Case

Jobs J_1 and J_2 can be "paired"

if $m_1 \le m_2$, $s_1 \ge s_2$, and $m_1+m_2=s_1+s_2$

(non-dominance) (balance)



Optimal schedule:

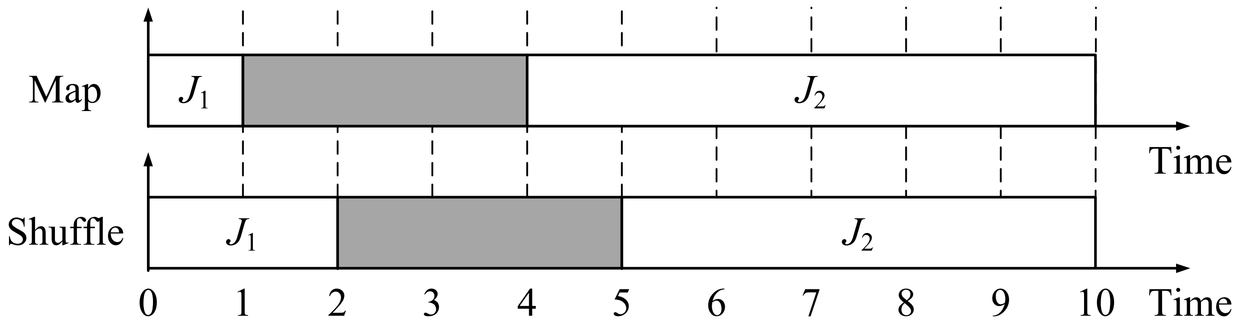
Pair jobs: shuffle-heavy before map-heavy

Sort job pair: by total workload m+s

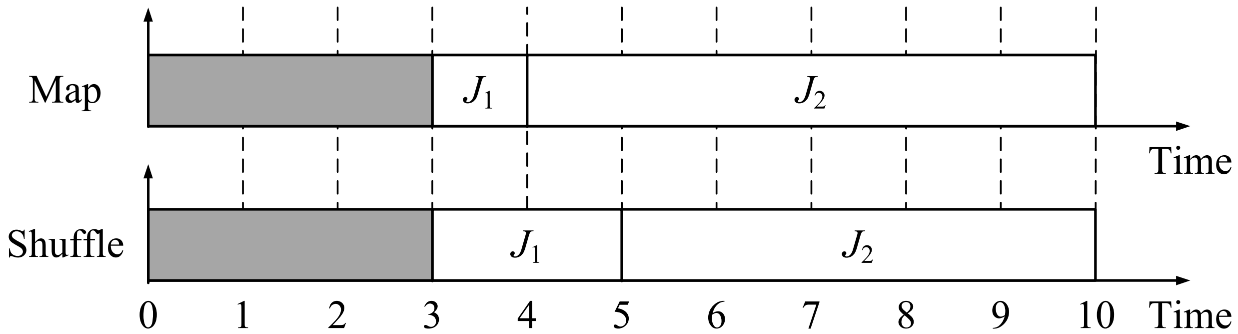
Execute smaller pairs earlier

Why Non-dominance?

Cannot pair small and large jobs J_1 and J_2



Completion times: 2, 5, and 10



Completion times: 3, 5, and 10

Theorem

If jobs can be paired, paired job scheduling is optimal if
(1) job pairs with smaller workloads are executed earlier and
(2) all pairs are executed together (shuffle-heavy first).

Proof ideas

In each pair, shuffle-heavy job is executed before map-heavy job
Otherwise a swap leads to a better result

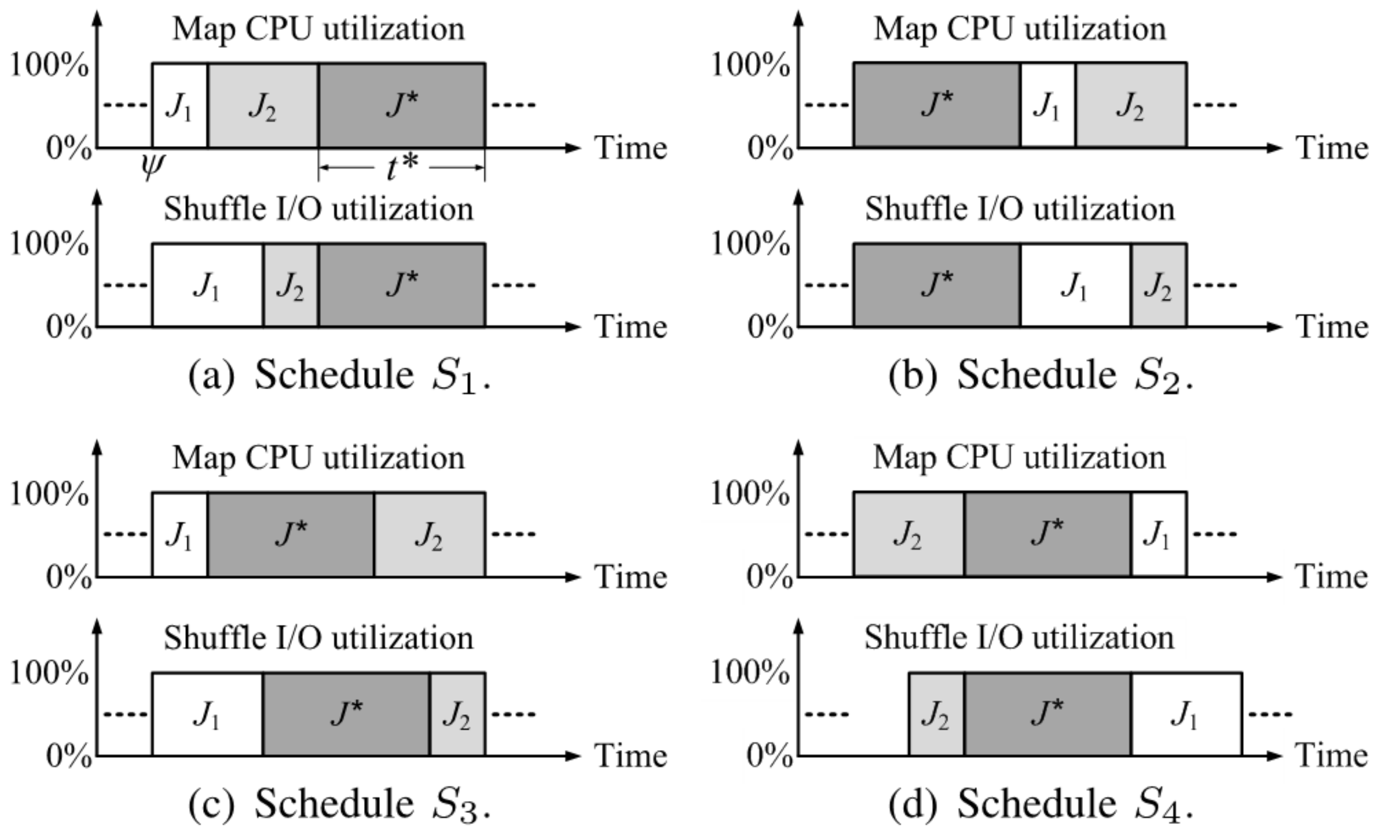
Job pairs with smaller total workloads are executed earlier
Otherwise a swap leads to a better result

Paired jobs should not be separately executed (a bit more involved)

Proof

S_1 is better than S_3 and S_4 when J^* is large

S_2 is better than S_3 and S_4 when J^* is small



(a) Schedule S_1.

(b) Schedule S_2.

(c) Schedule S_3.

(d) Schedule S_4.

3. First General Algorithm

Sort jobs based on their sizes ("workload")

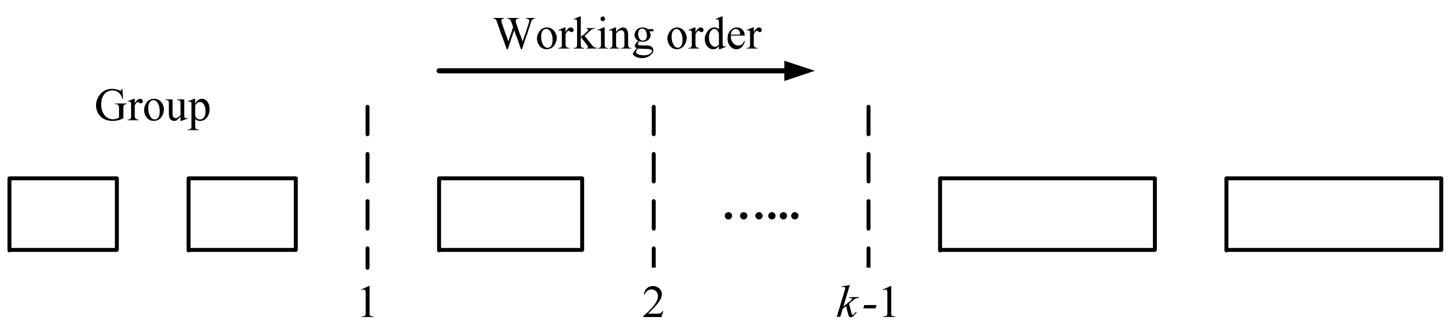
Partition sorted list in k (group factor) groups

Execute each group in order based on workload

Order matters for inter-group!

Pair jobs in each group

Pairing matters for intra-group!

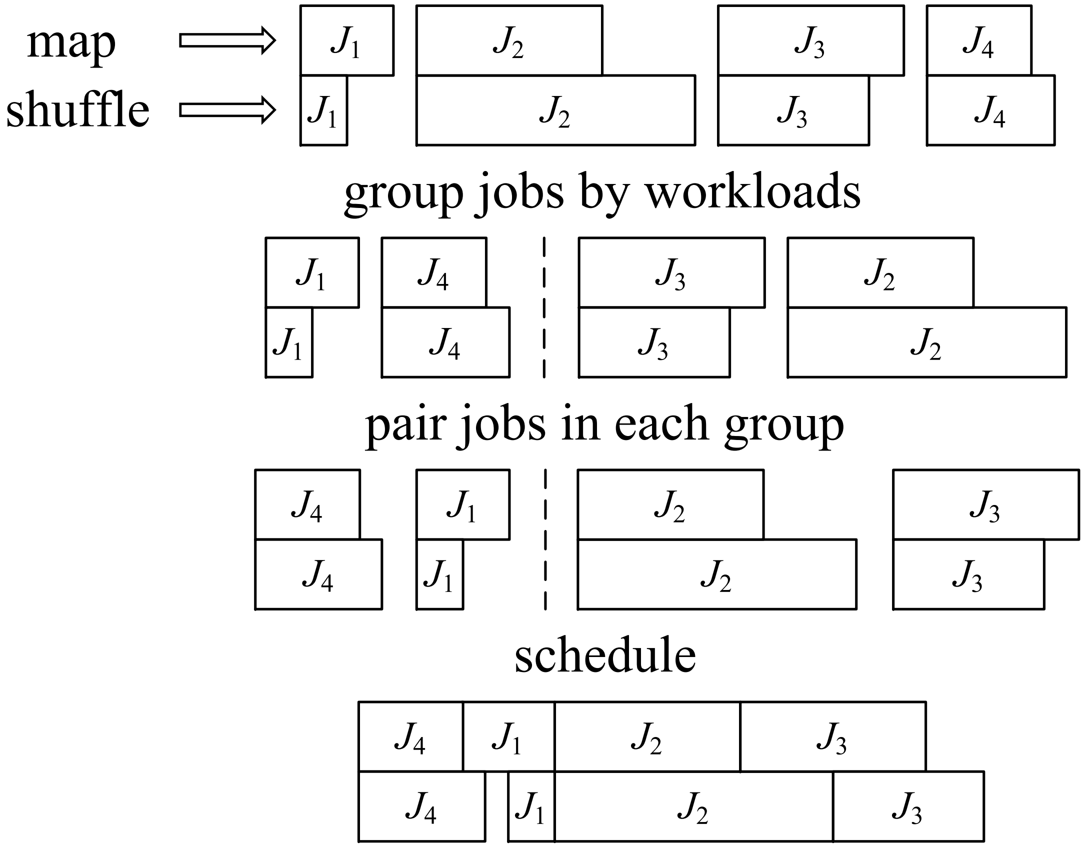


Group-Based Scheduling Policy (GBSP)

- Group jobs by their workloads (first factor)
  - Optimally divide jobs into k groups
    - minimize the sum of maximum job workload difference in each group
  - Execute the group of smaller jobs earlier
- Pair jobs in each group (second factor)
  - Jobs in each group have similar workloads
  - Pair shuffle-heaviest and map-heaviest jobs
- Time complexity is $O(n^2k)$

Example 1

Group-based scheduling policy



Workload Definition

- Dominant workload scheduling policy (DWSP)
  - Groups jobs by dominant workloads, max (m, s)
  - Performs well when jobs are simultaneously map-heavy, balanced, or shuffle-heavy
- Total workload scheduling policy (TWSP)
  - Groups jobs by total workloads, m+s
  - Performs well when jobs can be perfectly paired
- Weighted workload scheduling policy (WWSP)
  - A tradeoff between DWSP and TWSP
  - Groups jobs by weighted workloads , α*max(m,s) + (1-α)*(m+s)

Second Algorithm Design

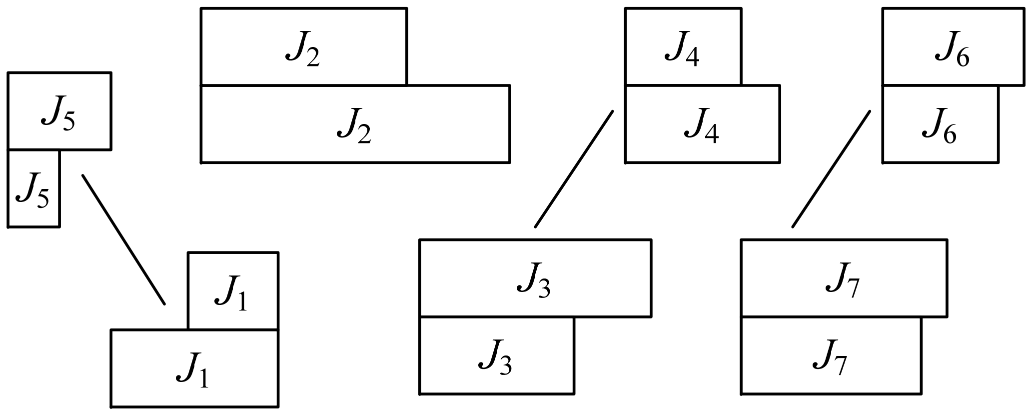
Pair jobs through minimum weight maximum matching

Matching weight for J_1 and J_2:

β * balance factor + (1-β) * non-dominance factor

Balance factor: $\frac{|m_1+m_2-s_1-s_2|}{m_1+m_2+s_1+s_2}$

Non-dominance factor: $\mathbb{1}_{(m_1-m_2)(s_1-s_2)\geq 0}$



Match-Based Scheduling Policy (MBSP)

- Sort jobs by map-shuffle workload difference
- Cut jobs into two parts
- Use minimum weight maximum matching to pair jobs in the second part
  - Exhaust all possible cuts and pick the best cut
- Sort jobs by their workloads after pairing
  - Paired jobs are regarded as one job

Map-dominant

Cut

Paired jobs | Single jobs

Sort jobs by m-s (↓ or ↑)

Shuffle-dominant

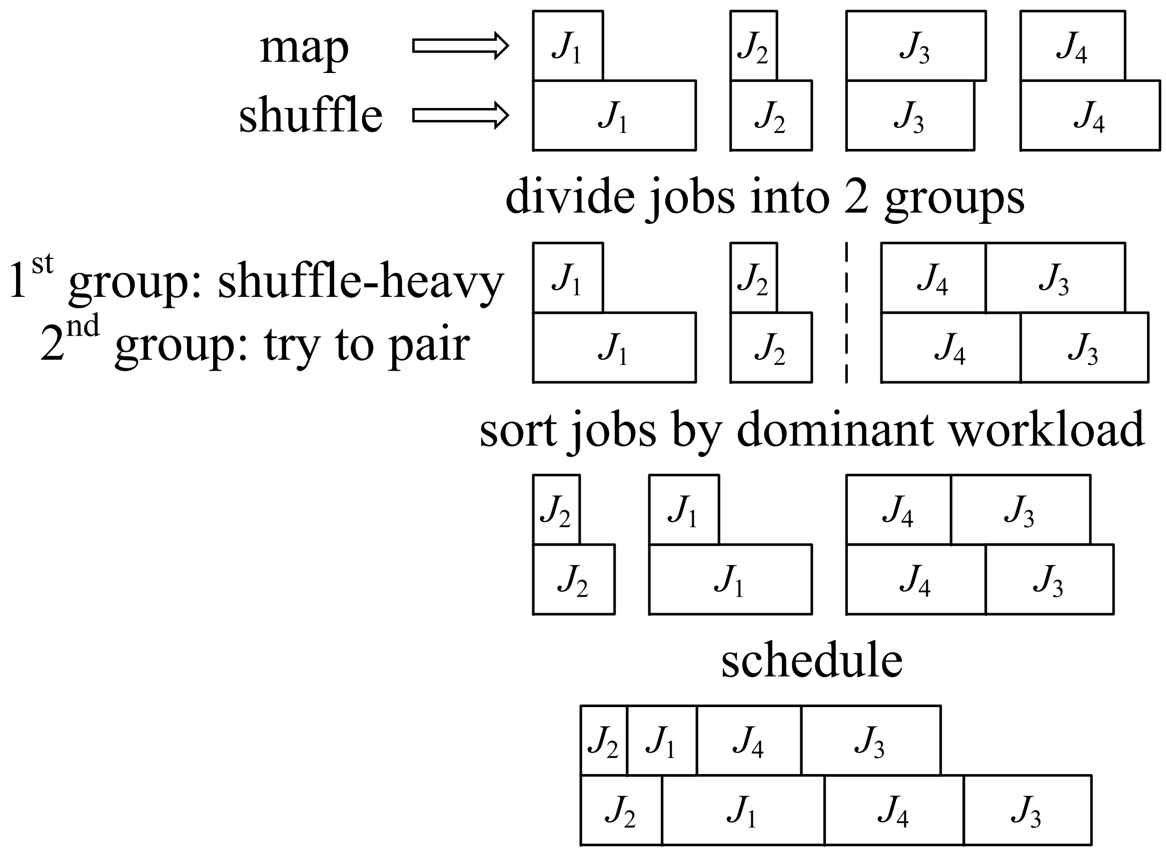
Cut

Paired jobs | Single jobs

Sort jobs by s-m (↓ or ↑)

Example 2

Match-based scheduling policy



Theorem

Match-based scheduling policy has an approximation ratio of 2 if

- (1) some jobs can be perfectly paired,
- (2) all remaining jobs are map-heavy, balanced, or shuffle-heavy,
- (3) dominant workload is used to sort jobs.

Time complexity is $O(n^{3.5})$

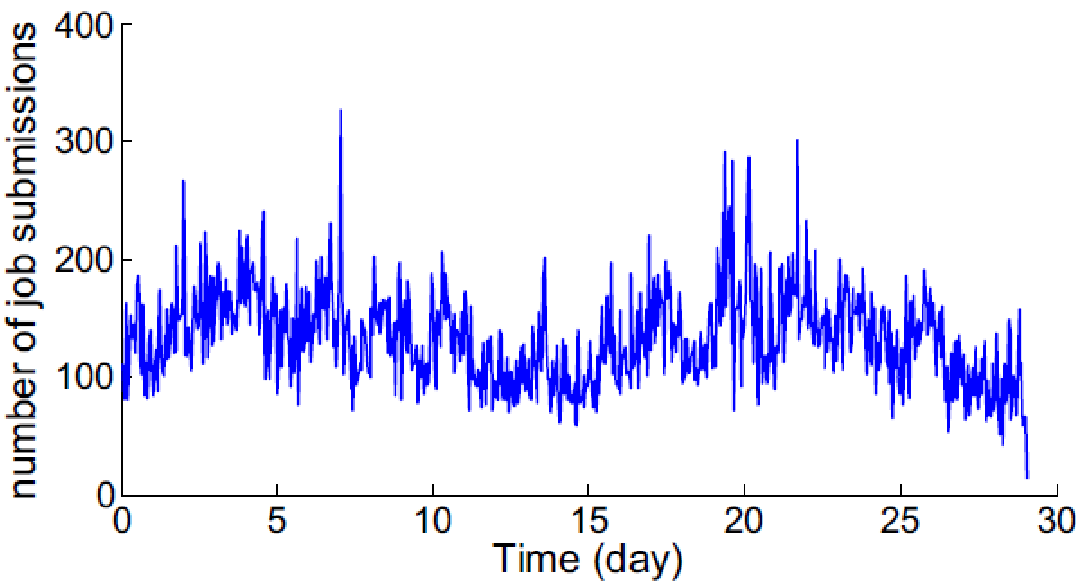
- Exhausting all cuts takes $O(n)$ iterations
- Matching in each iteration takes $O(n^{2.5})$

4. Experiment

Google Cluster Simulation

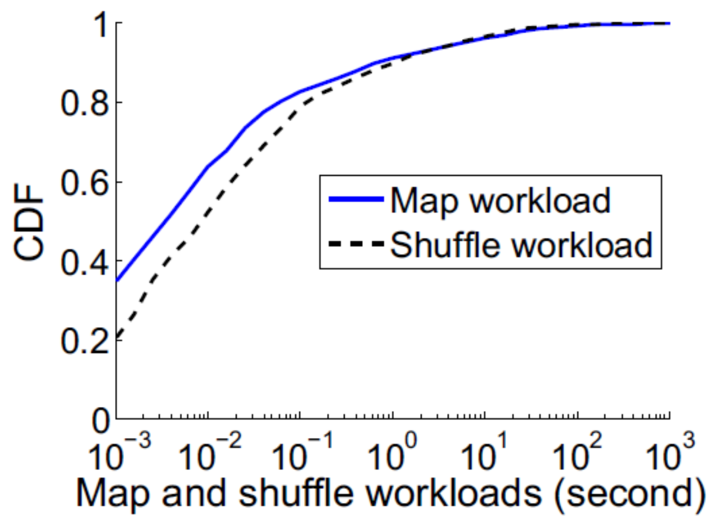
- About 11,000 machines
- 96,182 jobs over 29 days in May 2011

Number of job submissions per hour (arrival rate)

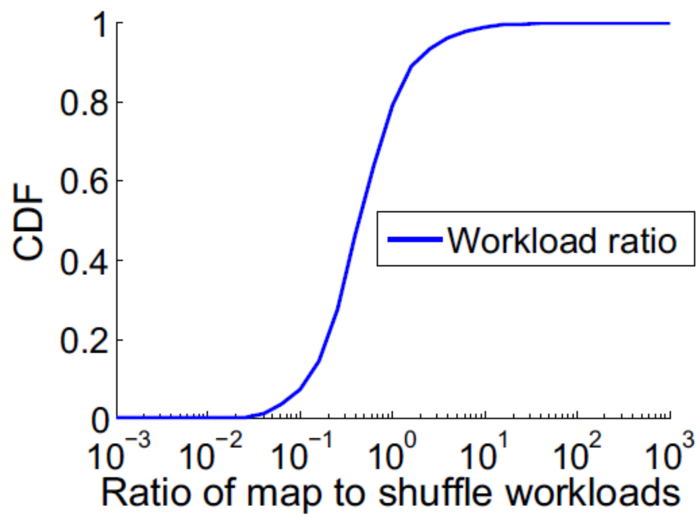


Google Cluster Dataset

Distribution of map and shuffle time



(a) Map and shuffle workloads.



(b) Workload ratio distribution.

Slightly more map-heavy jobs

Comparison Algorithms

Pairwise: has only one group then iteratively pairs the map-heaviest and shuffle-heaviest jobs in the group

MaxTotal: ranks jobs by total workload m+s and executes jobs with smaller total workloads earlier

MaxSRPT: ranks jobs by dominant workload max{m,s} and executes jobs with smaller dominant workloads earlier

Waiting, Execution, and Completion

Results (group k = 20, weight α = 0.5, β = 0.5)

	Scheduling algorithms	Average job waiting time			Average job execution time			Average job completion time		
	$\alpha/(\alpha+\beta)$	50%	75%	25%	50%	75%	25%	50%	75%	25%
	Pairwise	8289	7652	3609	149	23	28	8438	7675	3637
	MaxTotal	5054	4586	2525	362	32	156	5416	4618	2681
	MaxSRPT	4768	4546	2591	840	32	150	5608	4578	2741
GBSP	DWSP	4809	4519	2545	581	53	85	5390	4572	2630
GBSP	TWSP	4787	4501	2522	563	49	104	5350	4550	2626
GBSP	WWSP	4619	4482	2479	532	45	079	5151	4527	2558
	MBSP	4562	4314	2142	193	26	36	4340	4755	2178

Control job waiting time using the workload of each group

Control job execution time by pairing jobs within a group

The average job completion time ratio between MBSP and WWSP is 92.3%, 95.8% and 85.1%, respectively.

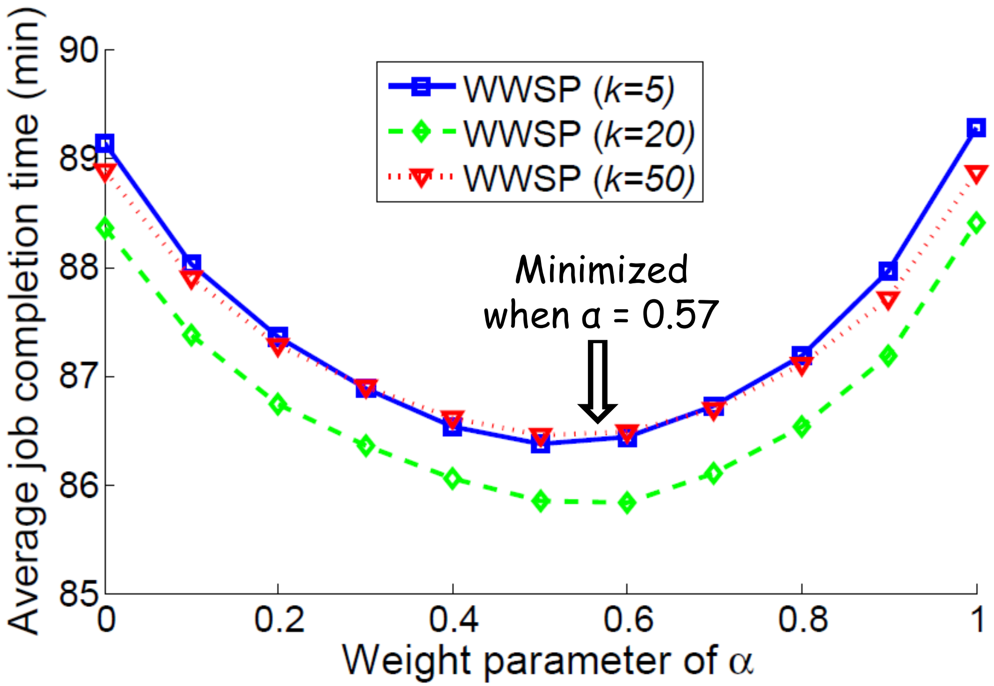
Impact of k and α in WWSP

Group-based scheduling policy with k groups

Sorts jobs by α*max(m,s) + (1-α)*(m+s)

Small/large group k

Small/large weight α

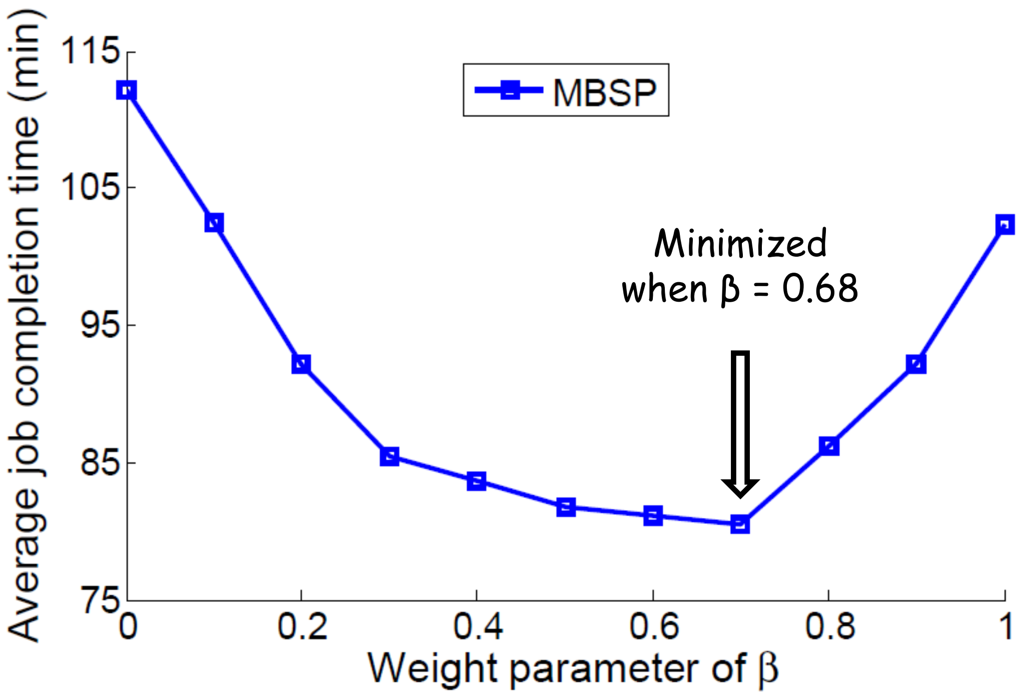


Impact of β in MBSP

Match-based scheduling policy matches J_1 and J_2 by

β * balance factor + (1-β) * non-dominance factor

Small/large weight β



Hadoop Testbed on Amazon EC2

Testbed

- Ubuntu Server 14.04 LTS (HVM)
- Single core CPU and 8G SSD memory

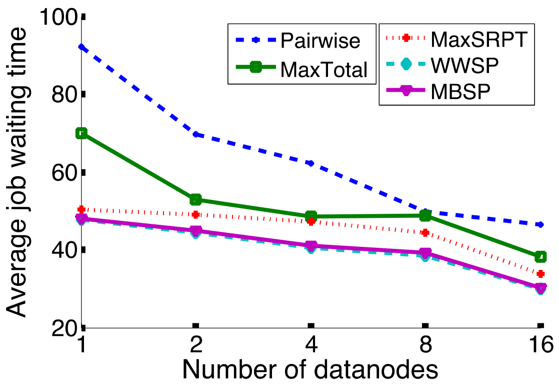
Jobs: WordCount jobs and TeraSort jobs

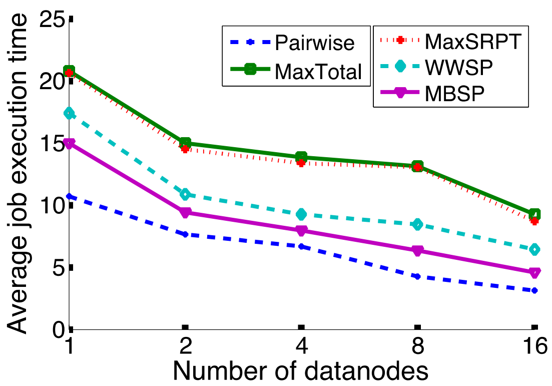
- 6 WordCount uses books of different sizes
  - 2MB, 4MB, 6MB, 8MB, 10MB, 12MB
- 6 TeraSort uses instances of different sizes
  - 1KB, 10KB, 100KB, 1MB, 10MB, 100MB

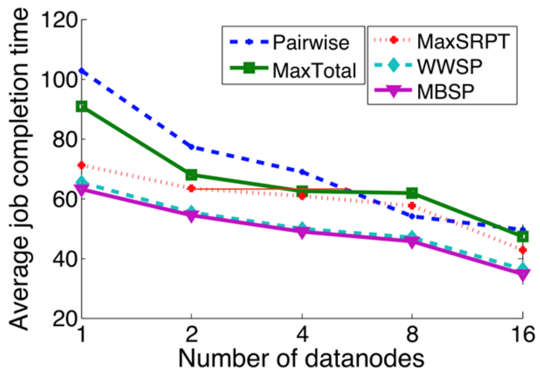
Waiting, Execution, and Completion

Hadoop: one master node + several data nodes

Number of data nodes: 1, 2, 4, 8, 16







MBSP has a slightly larger job waiting time than WWSP, but a smaller job makespan.

Performance Comparison

Pairwise has the smallest average execution time, but a large job wait time since workloads are ignored.

MaxTotal and MaxSPRT do not balance the trade-off between job sizes and job pairs.

DWSP, TWSP, WWSP, and MBSP jointly consider job sizes and job pairs.

5. Conclusion

Map and Shuffle phases can overlap

- CPU and I/O resource

Objective: minimize average job completion time

Group-based and match-based schedules

- Job workloads (dominant factor)
- Job pairs (avoid I/O underutilization)
- Optimality under certain scenarios

Future Work

Multiple phases

Beyond 2-phase

Batched online scheduling

Window-based approach

More simulations

Imbalanced map and shuffle

Impact of k, α, and β

More testbed cases

3-phase example