OPTIMIZING GOOGLE'S WAREHOUSE SCALE COMPUTERS:

THE NUMA EXPERIENCE

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Google

Warehouse Scale Computers

“Datacenters have become as vital to the functioning of society as power stations”
- *The Economist*

- Host large-scale Internet services (websearch, mail, etc)
- Expensive: hundreds of millions of dollars

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- Host large-scale Internet services (websearch, mail, etc)
- Expensive: hundreds of millions of dollars
- Efficiency is critical

Inefficiencies

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Inefficiencies

- Inefficiencies and missed optimization opportunities
  - Lack of understanding of interaction between applications and micro-architectural features/properties
  - Micro-architecture properties are abstracted away
    - a collection of thousands of cores, terabytes of main memory, petabytes of disk space, etc.
    - cannot adequately manage micro-architectural resources and features such as on-chip caches, non-uniform memory access, off-chip bandwidth, etc.

NUMA

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  - Old concept, yet limited understanding in new domain (new architectural implementations)
  - Software systems inadequate at effective management
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  - Old concept, yet limited understanding in new domain (new architectural implementations)
  - Software systems inadequate at effective management
  - Interaction between emerging applications in modern large scale WSCs unclear
- How do we understand the interaction?

Status-Quo

- Performance analysis in controlled environment
  - narrow focus; cannot replicate all aspects of the real production environment in a small-scale
  - miss the big picture
- Production study
  - Monitor datacenters with live services, interpret data

Challenges in Production Study

- Scale and complexity, intertwined performance factors
- Unknown factors, change spontaneously (load/user behavior, etc)
- Noisy performance data
- Inexplicable performance swing
  - 4x range of average request latency during a week's time for Gmail backend
- 1% performance improvement means millions

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  - 4x range of average request latency during a week's backend
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Difficult to reason about each individual microarchitectural factor' effect on applications

Methodology

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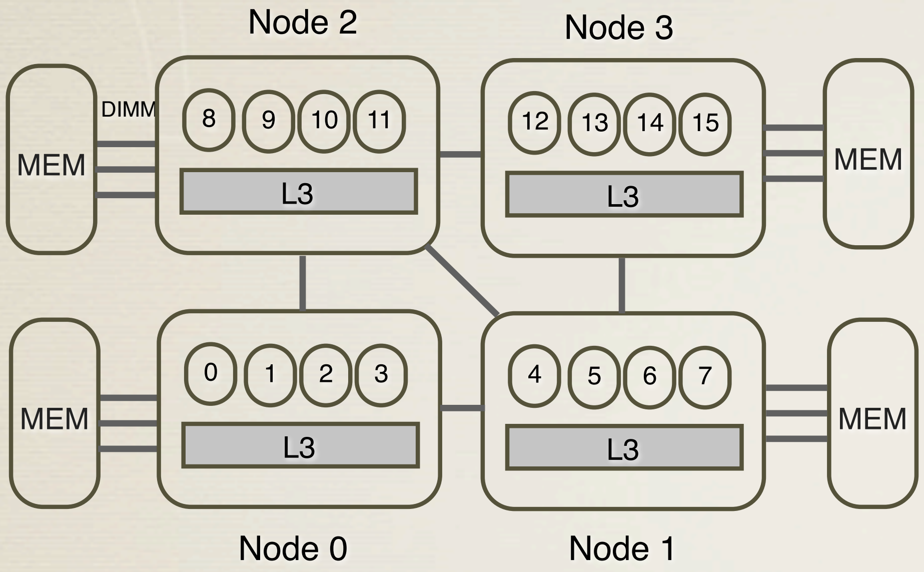
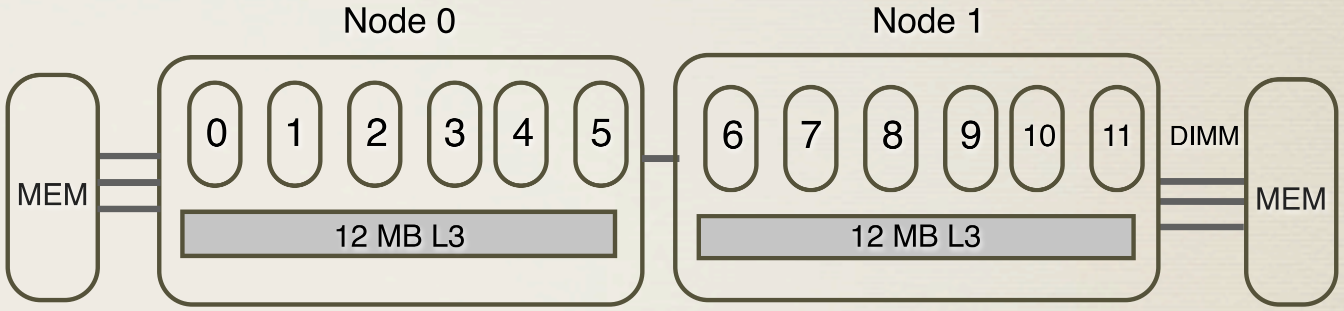
- NUMA
  - Performance impact of NUMA
  - Gmail backend and websearch frontend

NUMA (Non-Uniform Memory Access)



AMD Barcelona

- local memory
- 1-hop away
- 2-hop away



Intel Westmere

- local memory
- 1-hop away

Production Study

- What's the performance impact of NUMA in datacenters?
- What data to collect
  - **Metric**: to quantify the NUMA status
- How to collect them
  - **Profiling and monitoring:** lightweight, low overhead, for large-scale system
- How to interpret data
  - **Analysis**: Careful correlation and analysis of noisy data

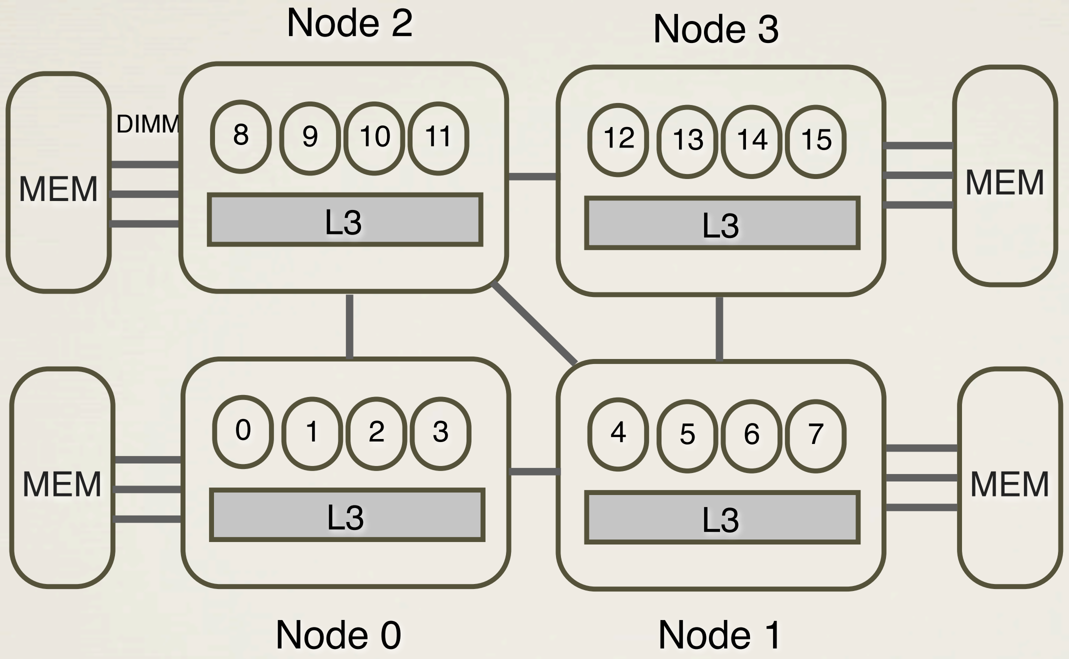
Metric: A job's NUMA Score

$$Score = \sum_{i=1}^{n} \sum_{j=1}^{n} C[i] \cdot M[j] \cdot \frac{D(i,i)}{D(i,j)}$$

- *C[i]:* normalized CPU usage for node *i*
- *M[j]:* normalized memory usage for node *j*
- *D(i,j):* distance between two nodes *i* and *j*

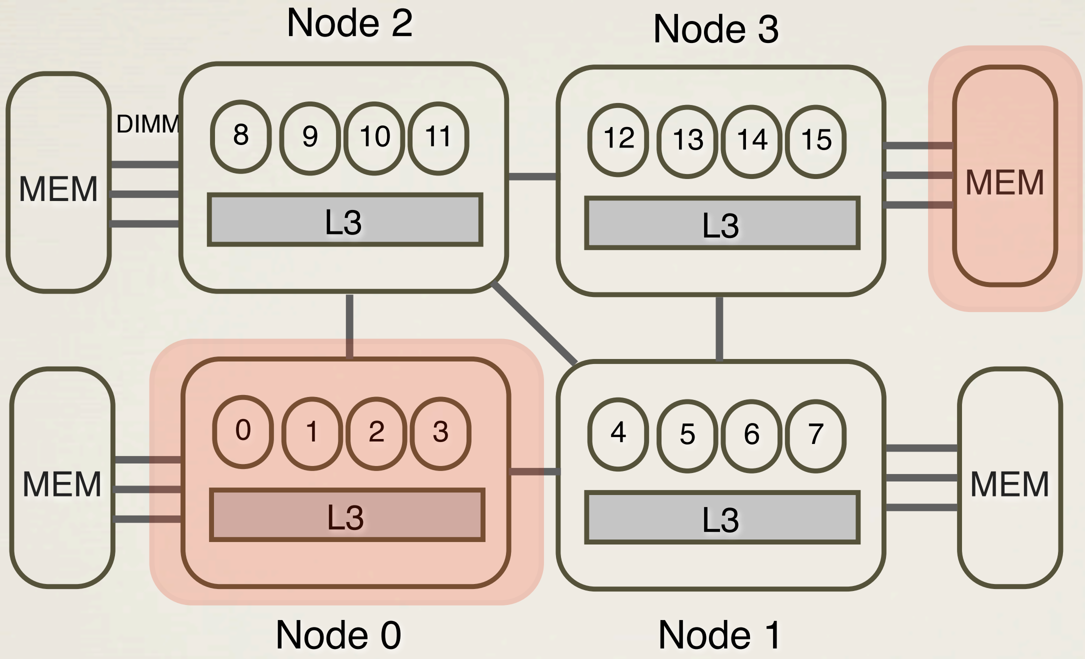
- between 0 and 1.
- allows low overhead profiling

NUMA Score: Example



- 100% accesses between Node 0 and 3: 0.33
- 100% between Node 0 and 2: 0.66
- 100% local : 1

NUMA Score: Example



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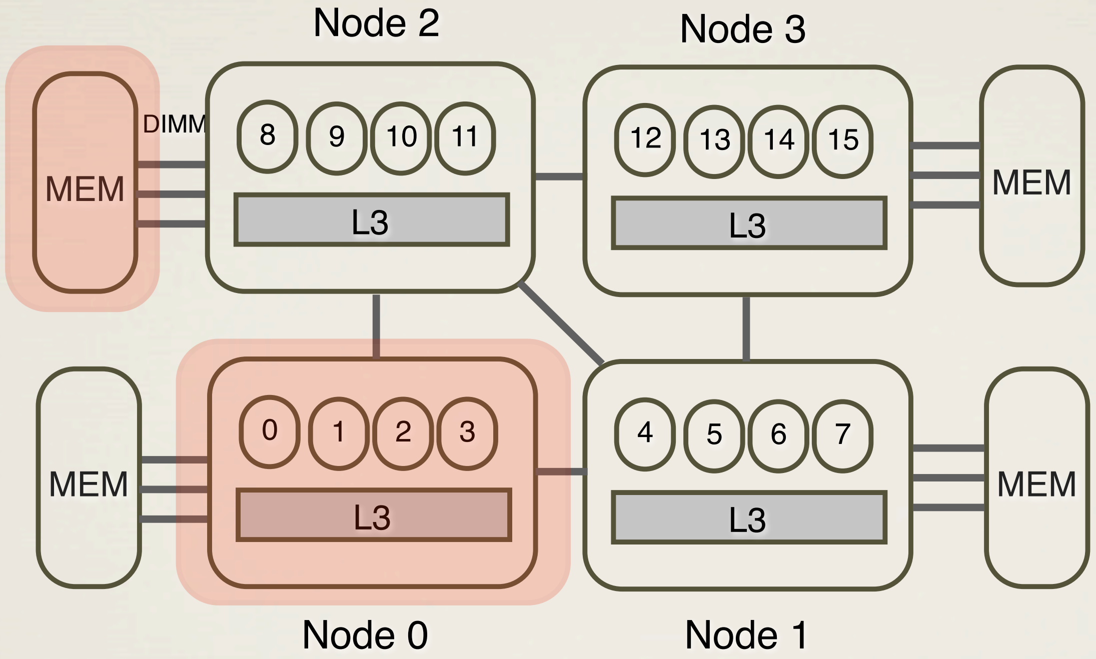

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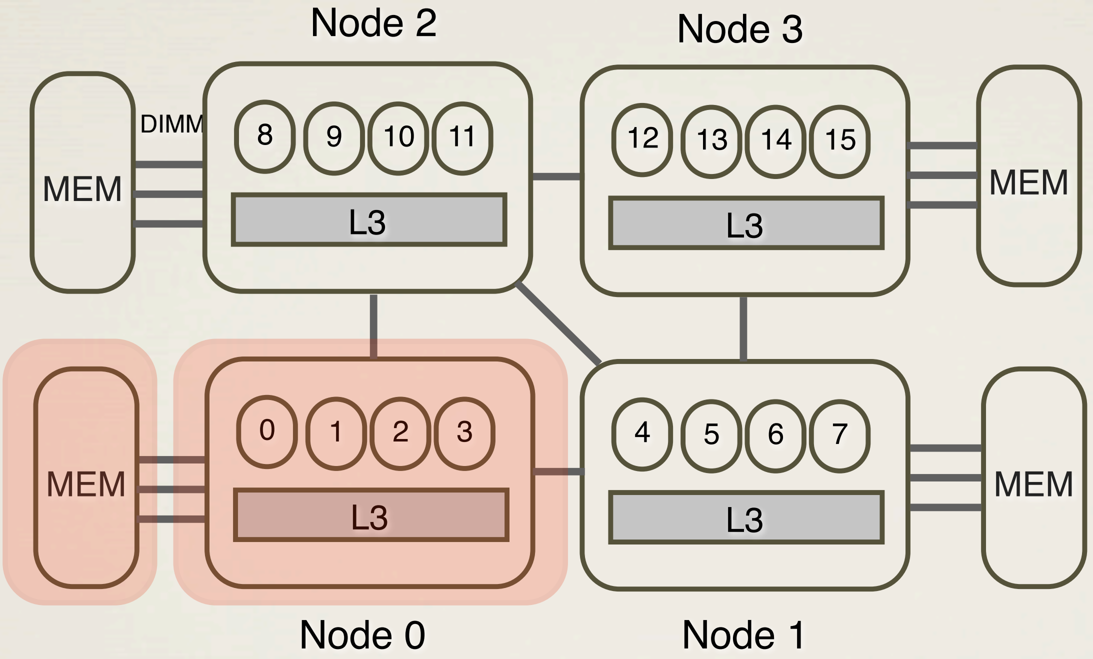

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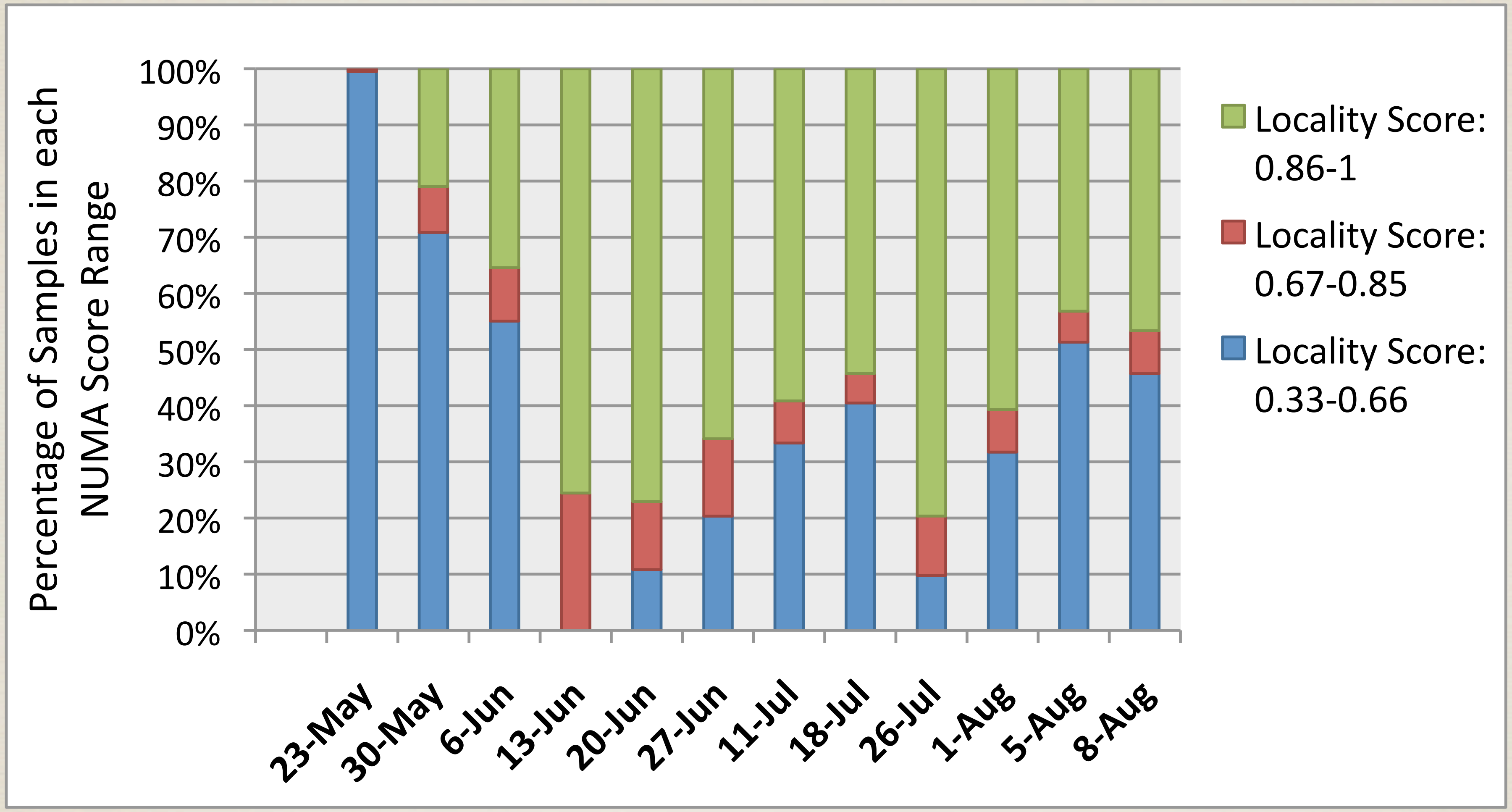
Profiling in Production

- Large-scale profiling/monitoring infrastructure in production
  - Example: Google Wide Profiling
- NUMA Score
- Performance metrics
  - CPI
  - Application-specific metrics

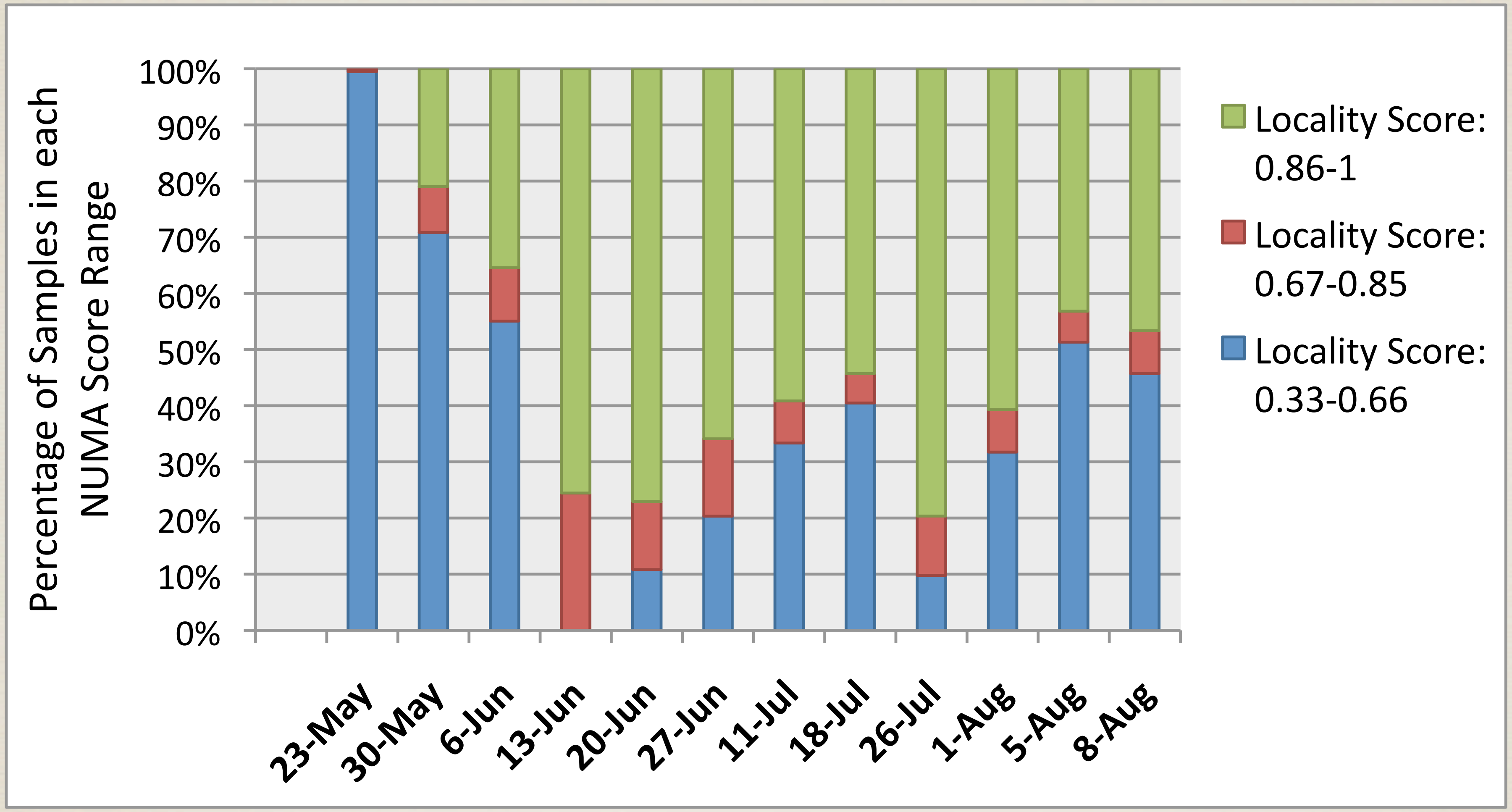
Gmail Backend

- Sticky service
- Running in co-located clusters
- Global datacenters
- Load balancer migrates user accounts
- Load fluctuates

NUMA Score Distribution

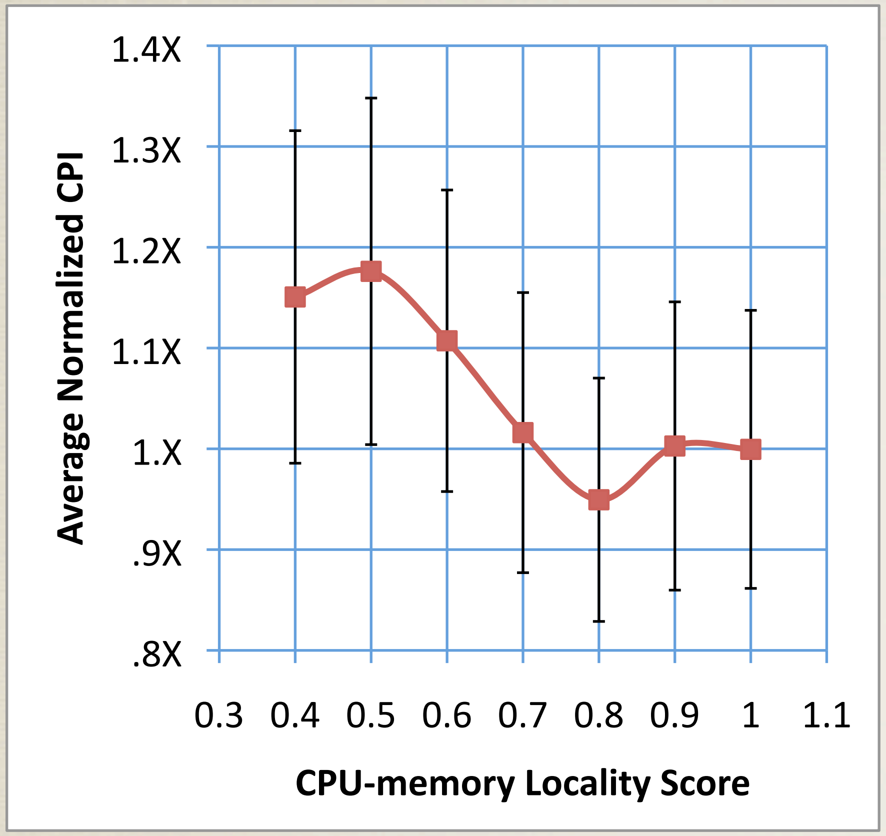


NUMA Score Distribution

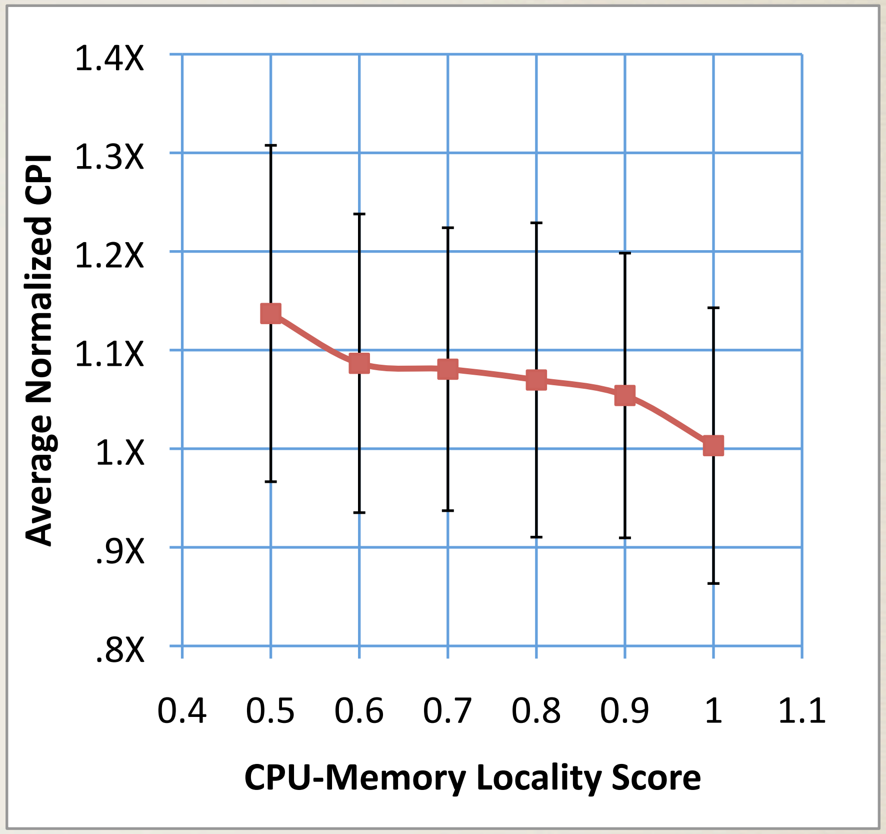


for a significant amount (often more than 50%) of jobs, all memory accesses are at least 1 hop away.

Gmail Backend



CPI vs. NUMA score 05/30.

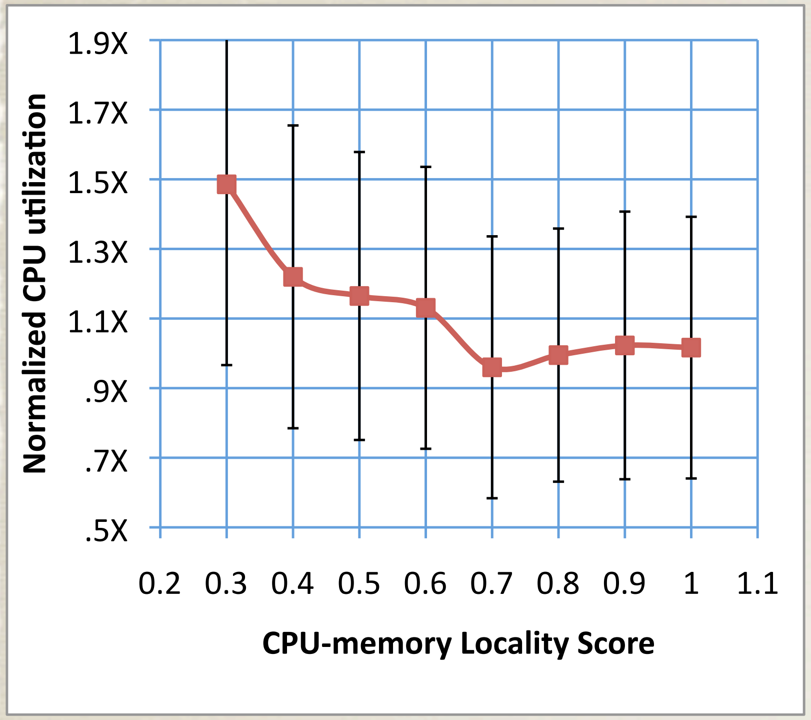


CPI vs. NUMA score on 06/20.

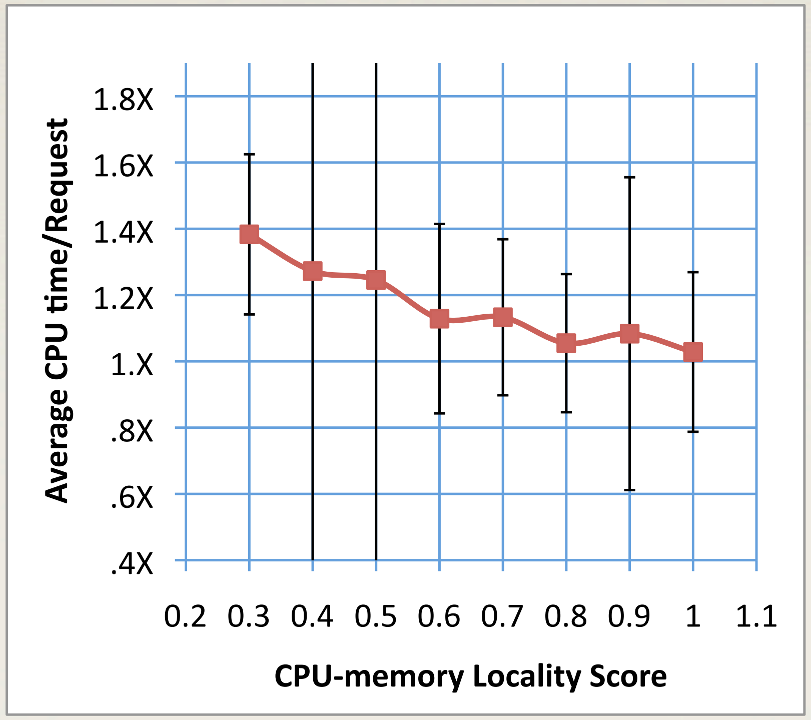
Better NUMA score correlates with lower CPI.

10-20% performance swing

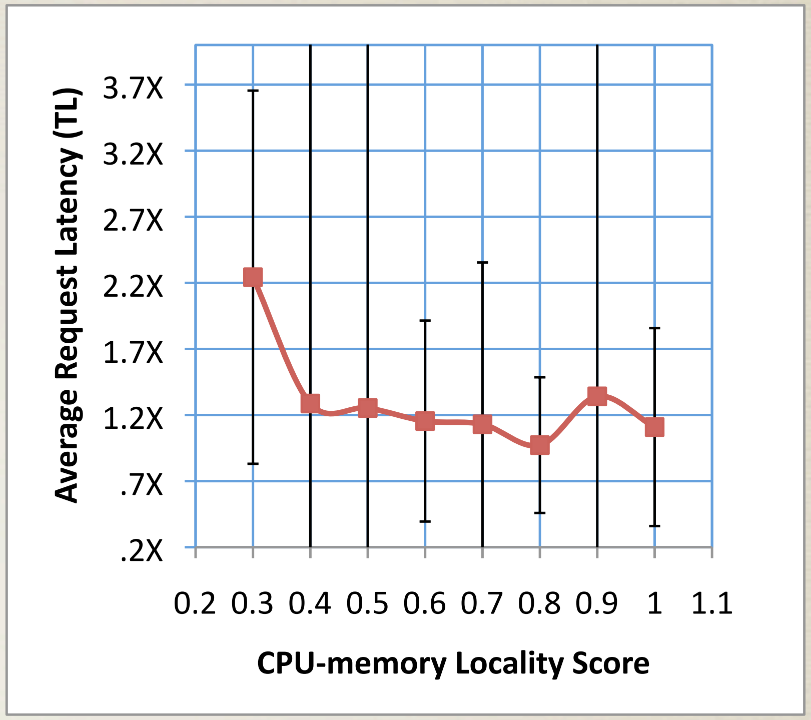
Gmail Backend



CPU utilization vs. NUMA



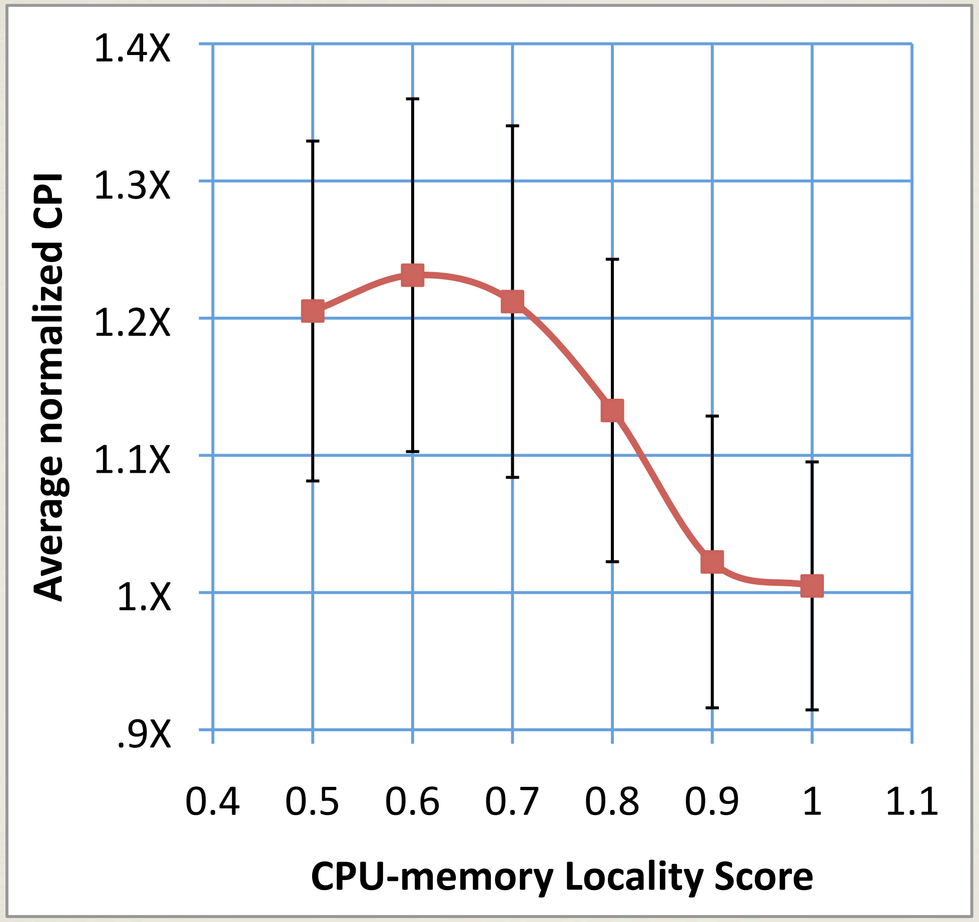
CPU time/request vs. NUMA



Request Latency (threadlist) vs. NUMA

- Better NUMA score correlates with lower CPU utilization.
- Noisy data for request latency and CPU/request

Websearch Frontend



CPI vs. NUMA score

Better NUMA score correlates with lower CPI.

~20% performance swing

Methodology

- 2-phase Methodology
  - Production study in the wild
  - Single-node load-test in the controlled environment

Load Test on Single Server

- Tradeoffs between **memory access locality** and the impact of **cache sharing/contention** on a CMP machine

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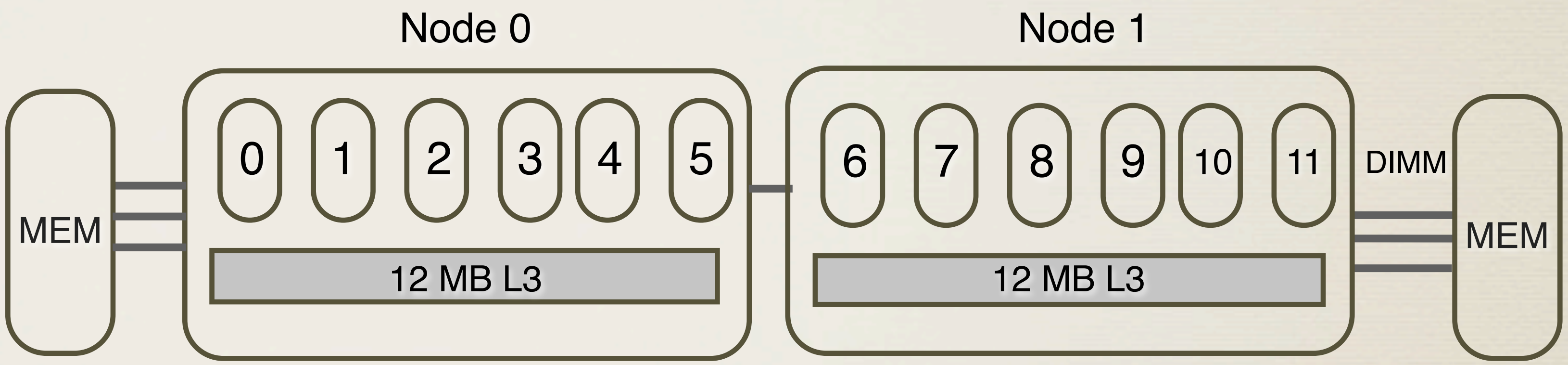

X solo:

1. 100% Local access, sharing 1 LLC
2. 50% Local access, sharing 2 LLCs
3. 0% Local access, sharing 1 LLC

	0	1	2	3	4	5	6	7	8	9	10	11
M-X	X	X	X	X	X	X						
M-X	X	X	X				X	X	X			
M-X							X	X	X	X	X	X

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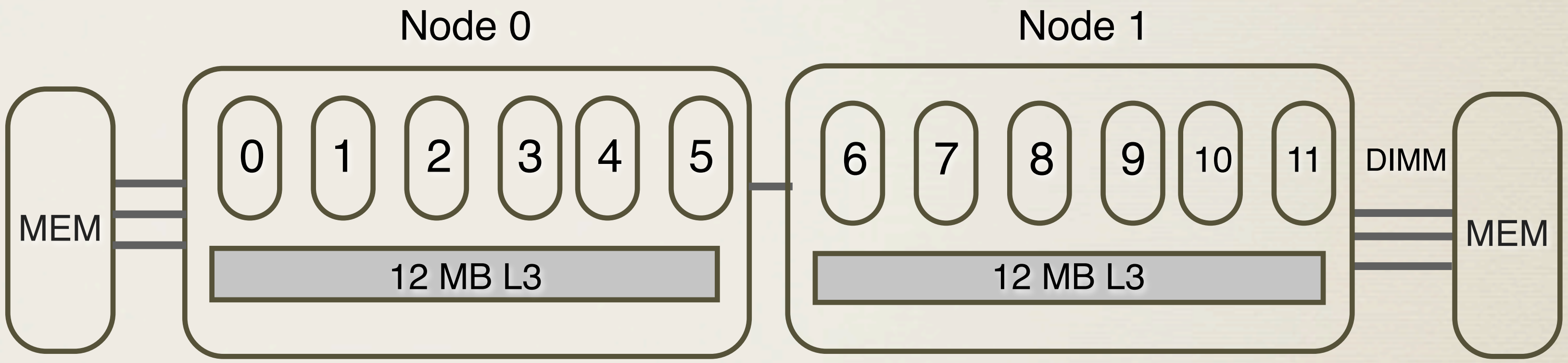

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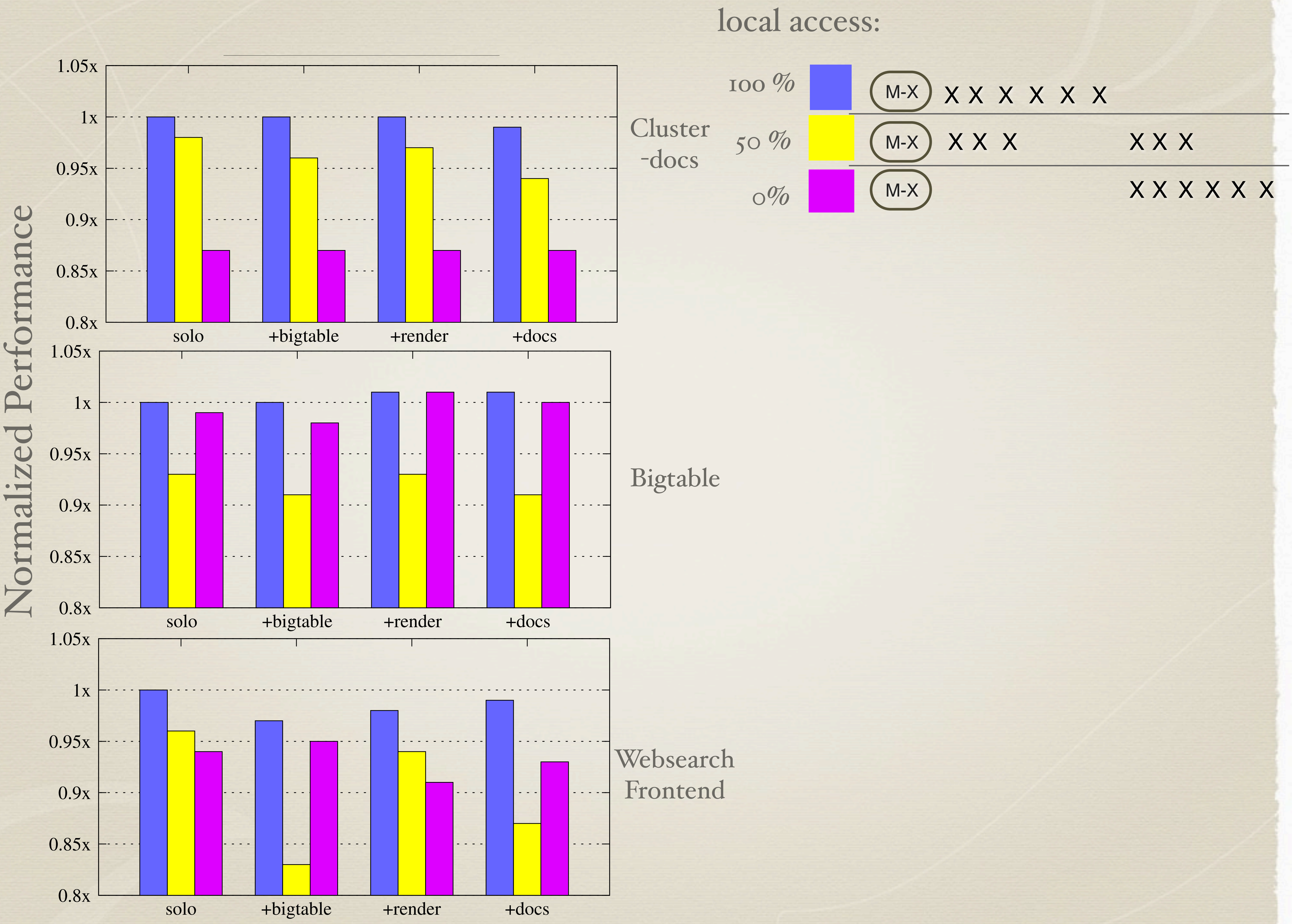
M-X	X	X	X	X	X	X							
M-X	X	X	X				X	X	X				
M-X							X	X	X	X	X	X	

X coruns w/ Y:

4. 100 % Local access, sharing LLC w/ sibling
5. 50 % Local access, sharing LLC w/ Y
6. 0 % Local access, sharing LLC w/ sibling

M-X	X	X	X	X	X	X	Y	Y	Y	Y	Y	Y	M-Y
M-X	X	X	X	Y	Y	Y	X	X	X	Y	Y	Y	M-Y
M-X	Y	Y	Y	Y	Y	Y	X	X	X	X	X	X	M-Y

local access:
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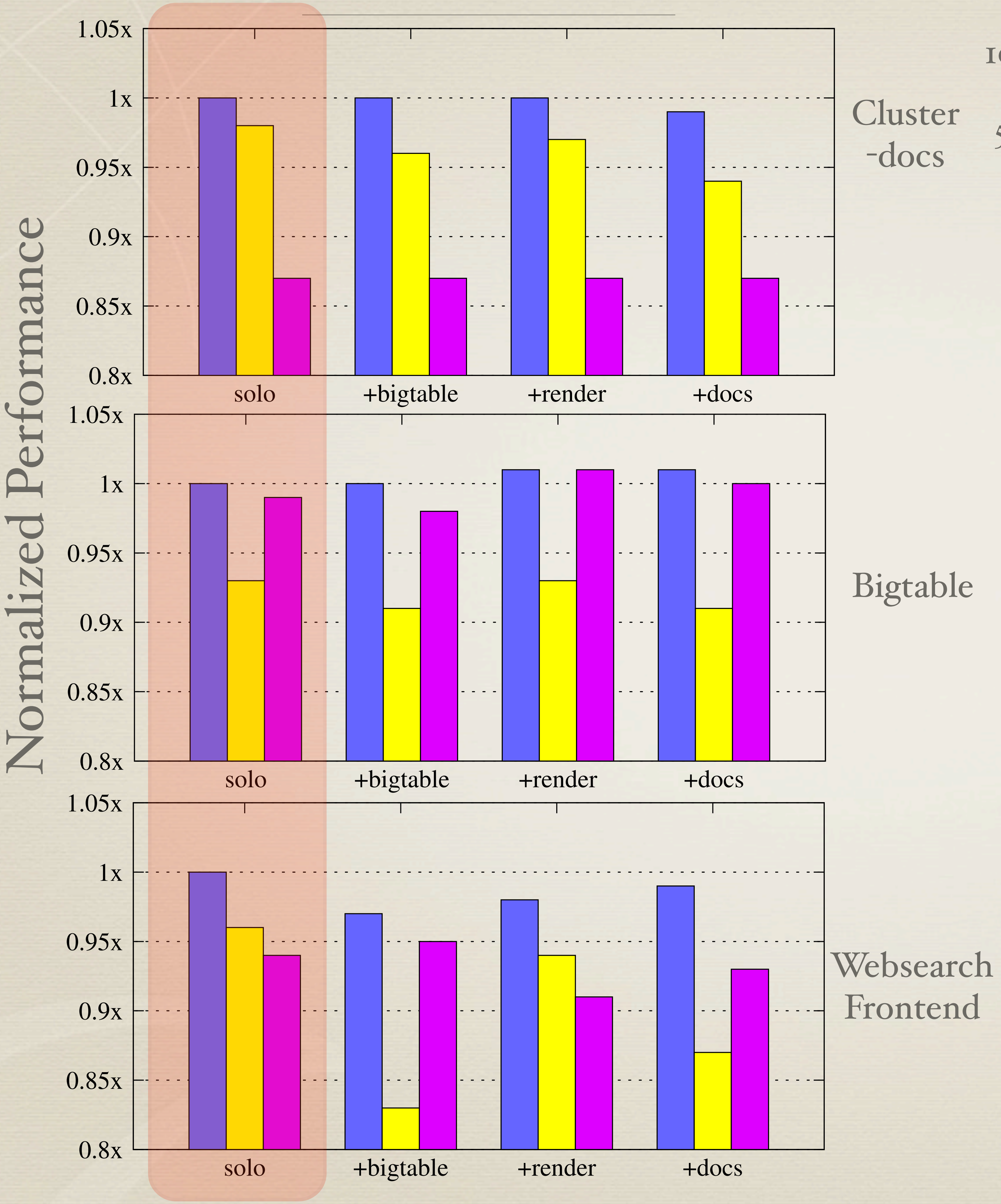
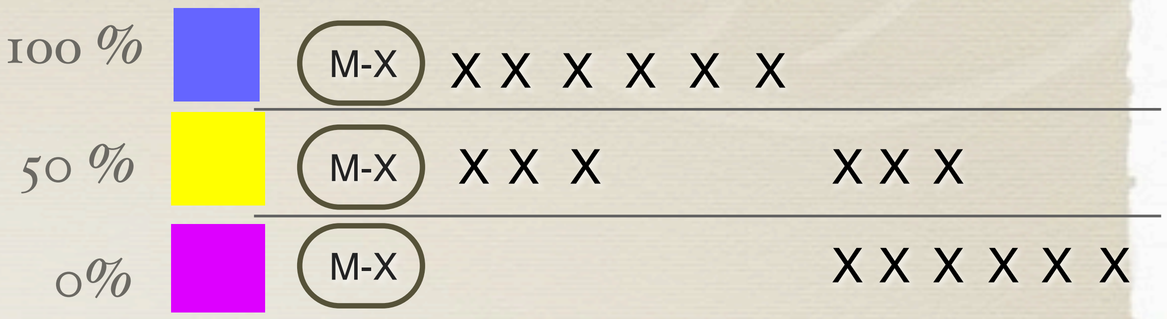
Bigtable
Websearch Frontend

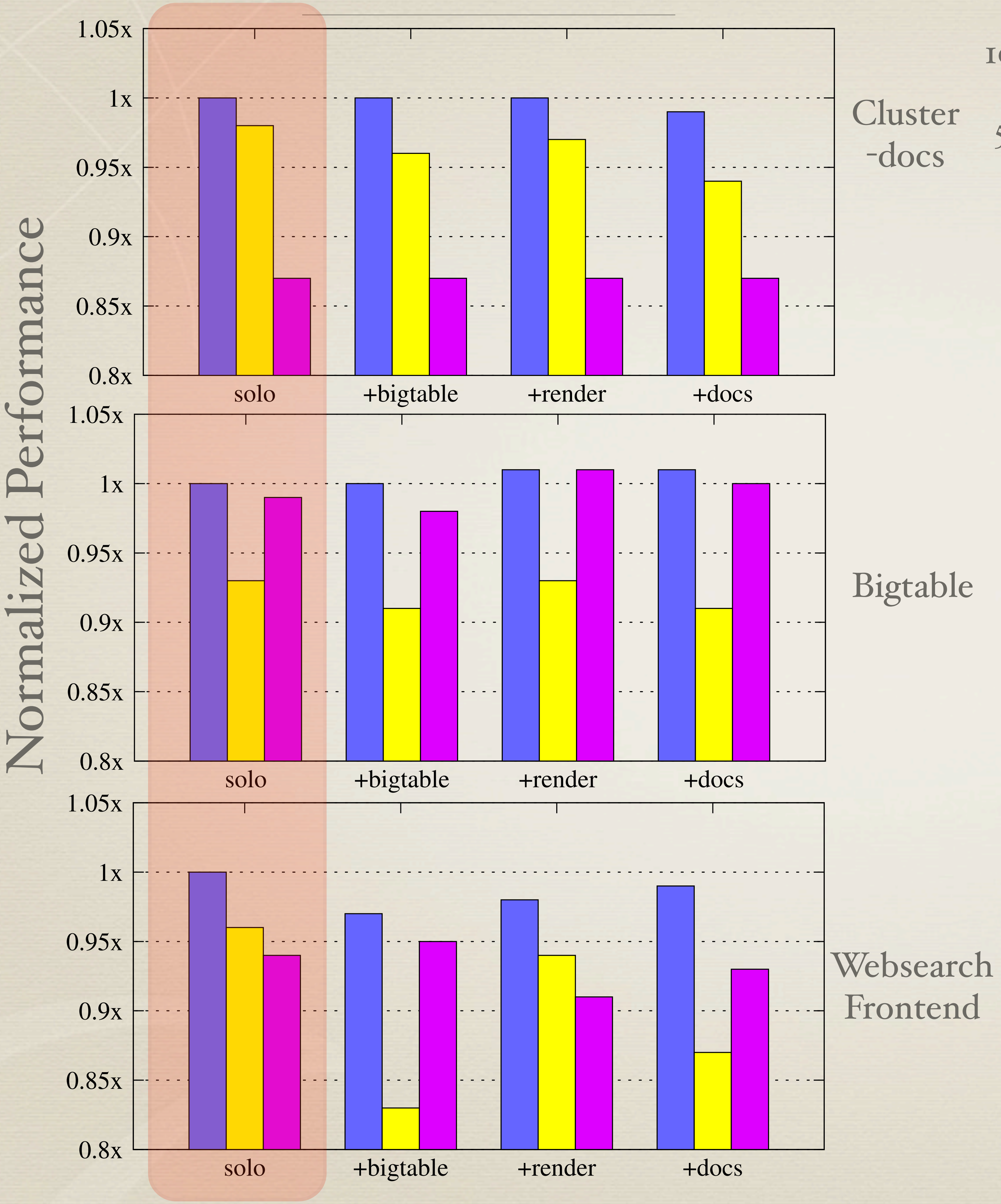
Solo



local access:



Solo



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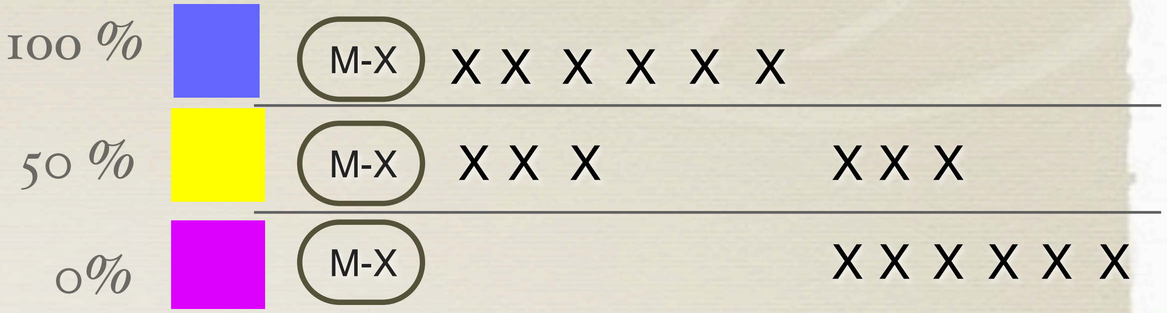
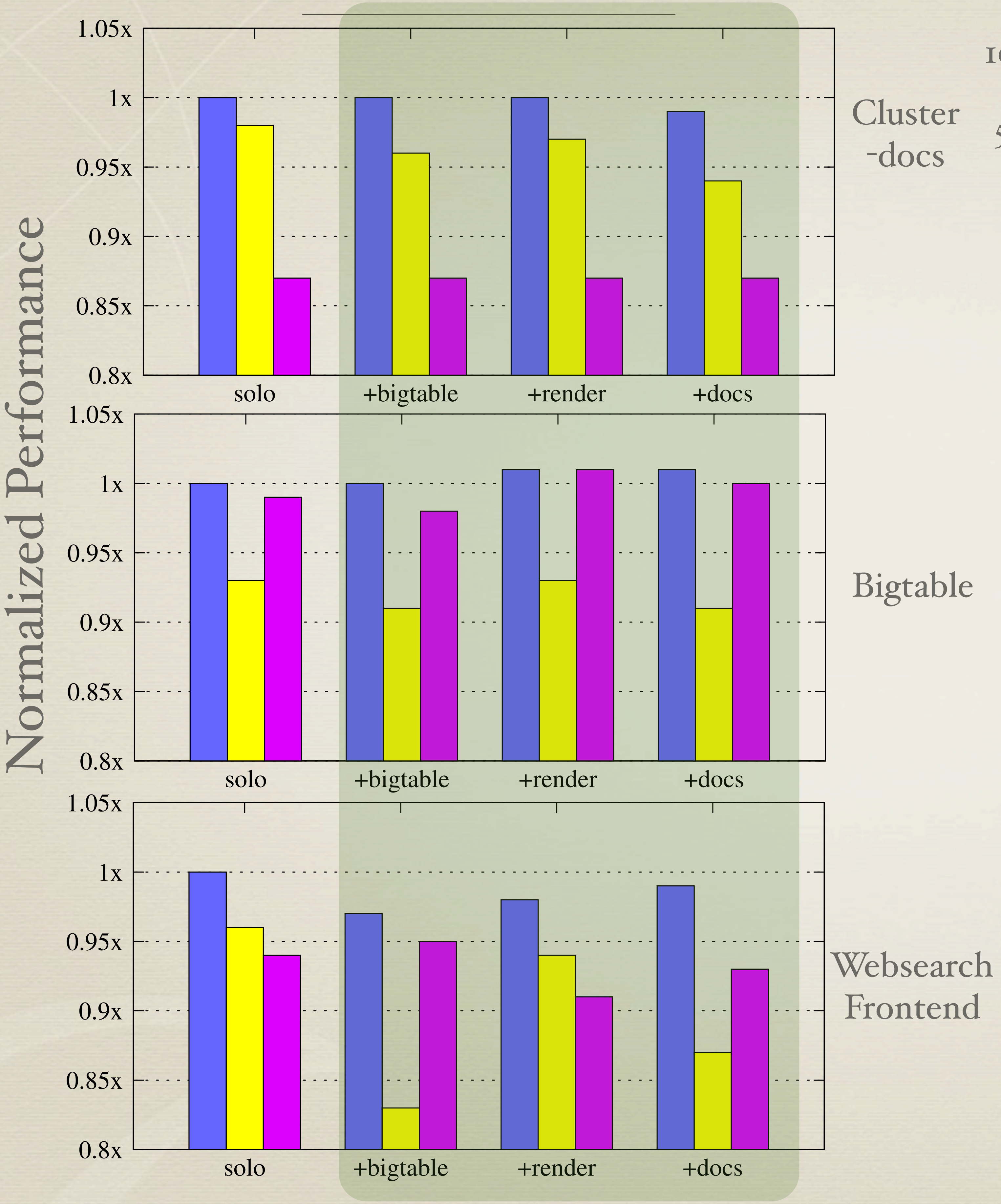
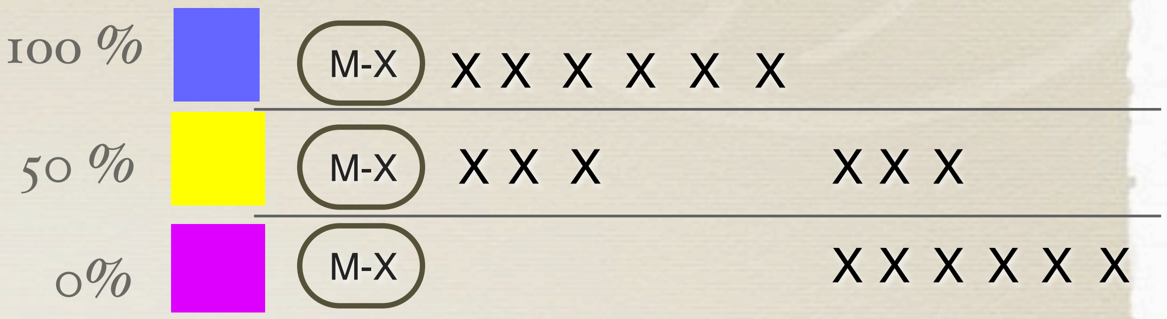


- Solo:
  - bigtable 0% local access outperform 50% local access

Corun



local access:



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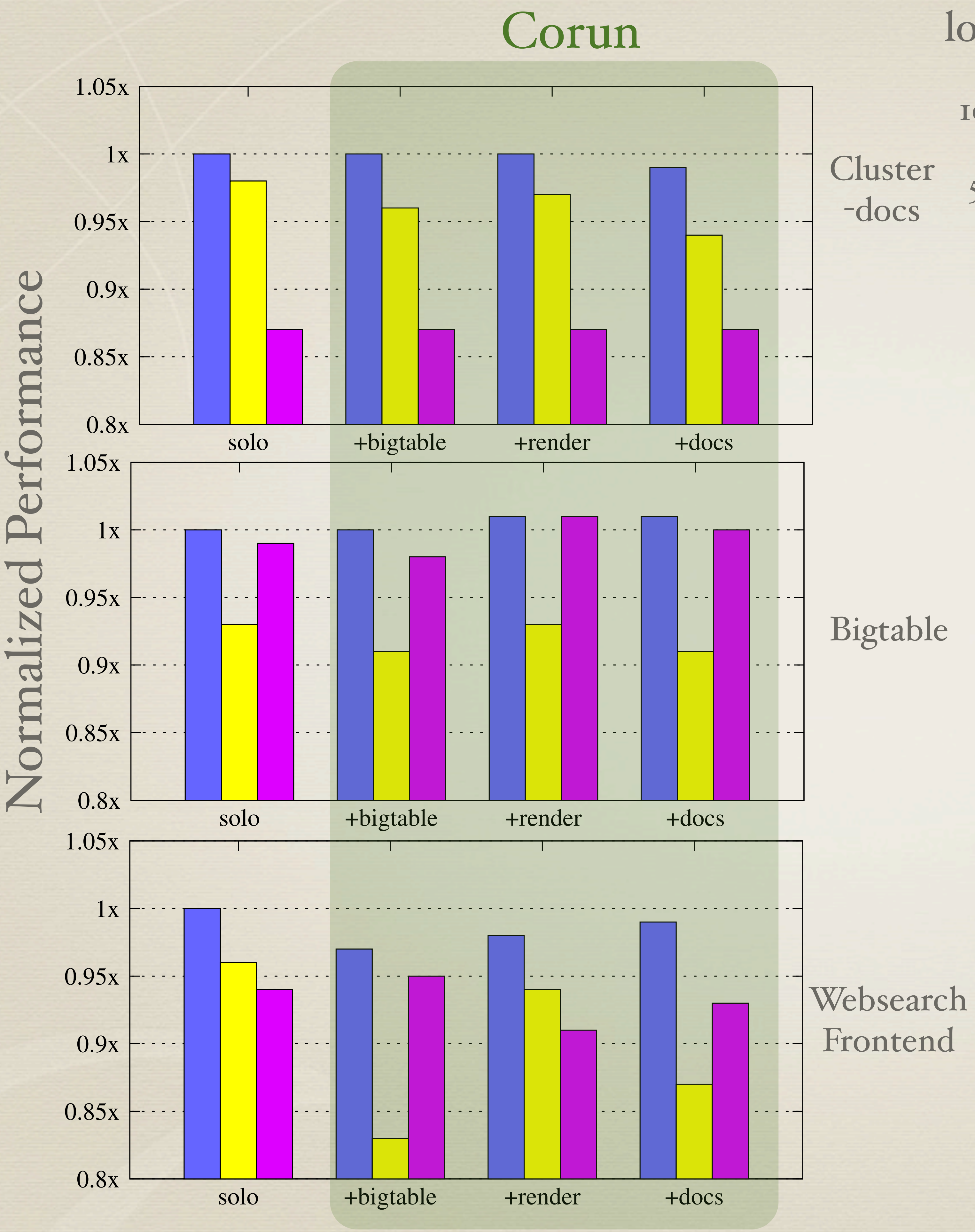
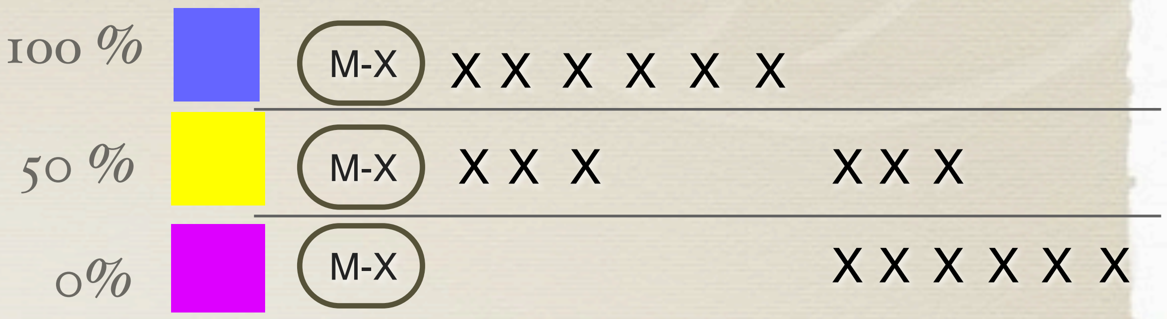


local access:



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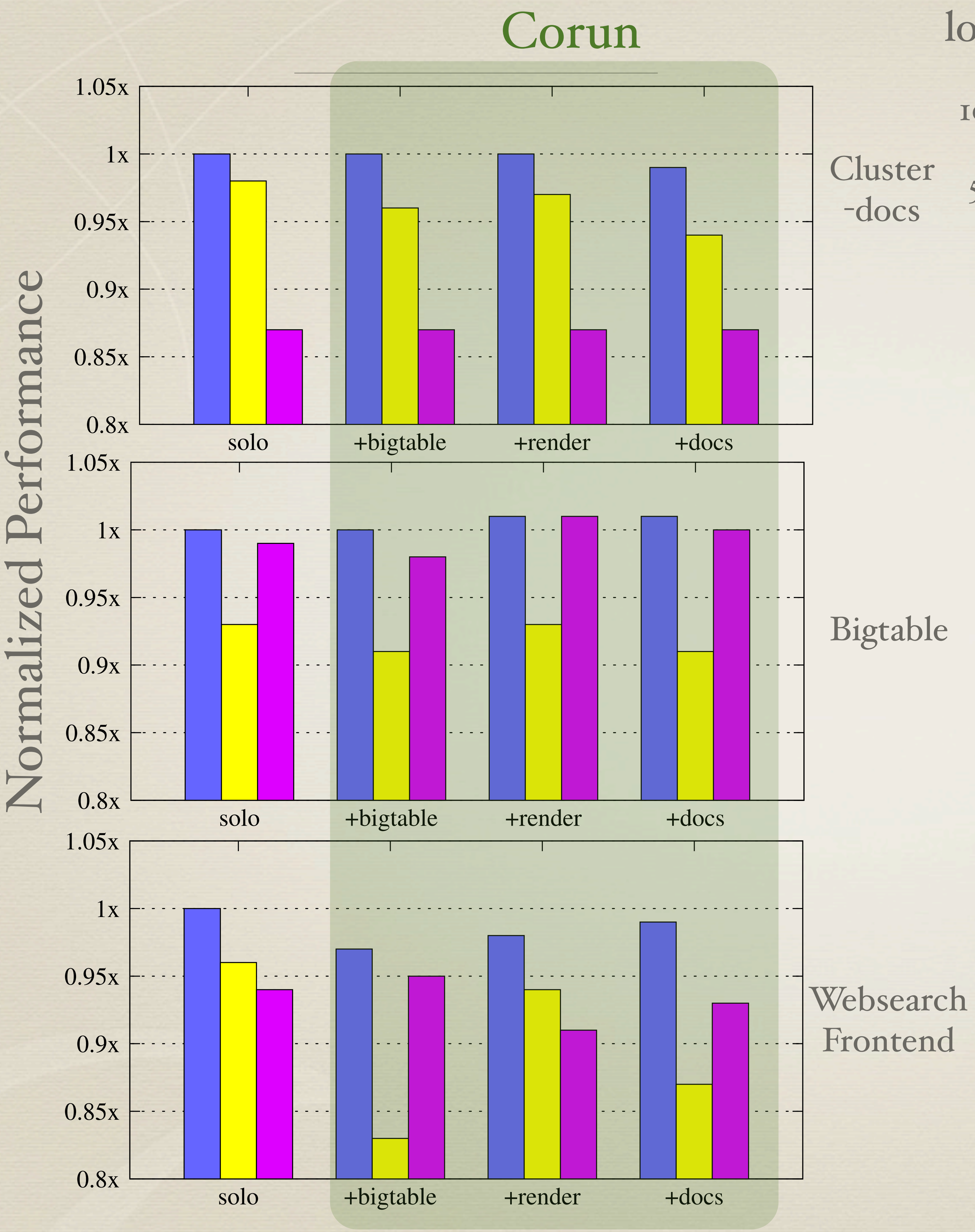

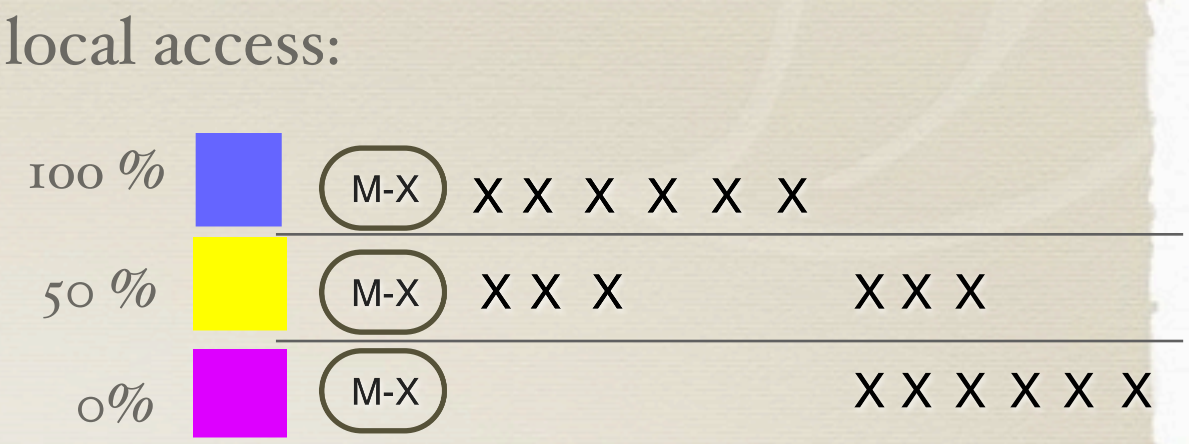

- Solo:
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tradeoffs b/t NUMA and cache sharing/ contention

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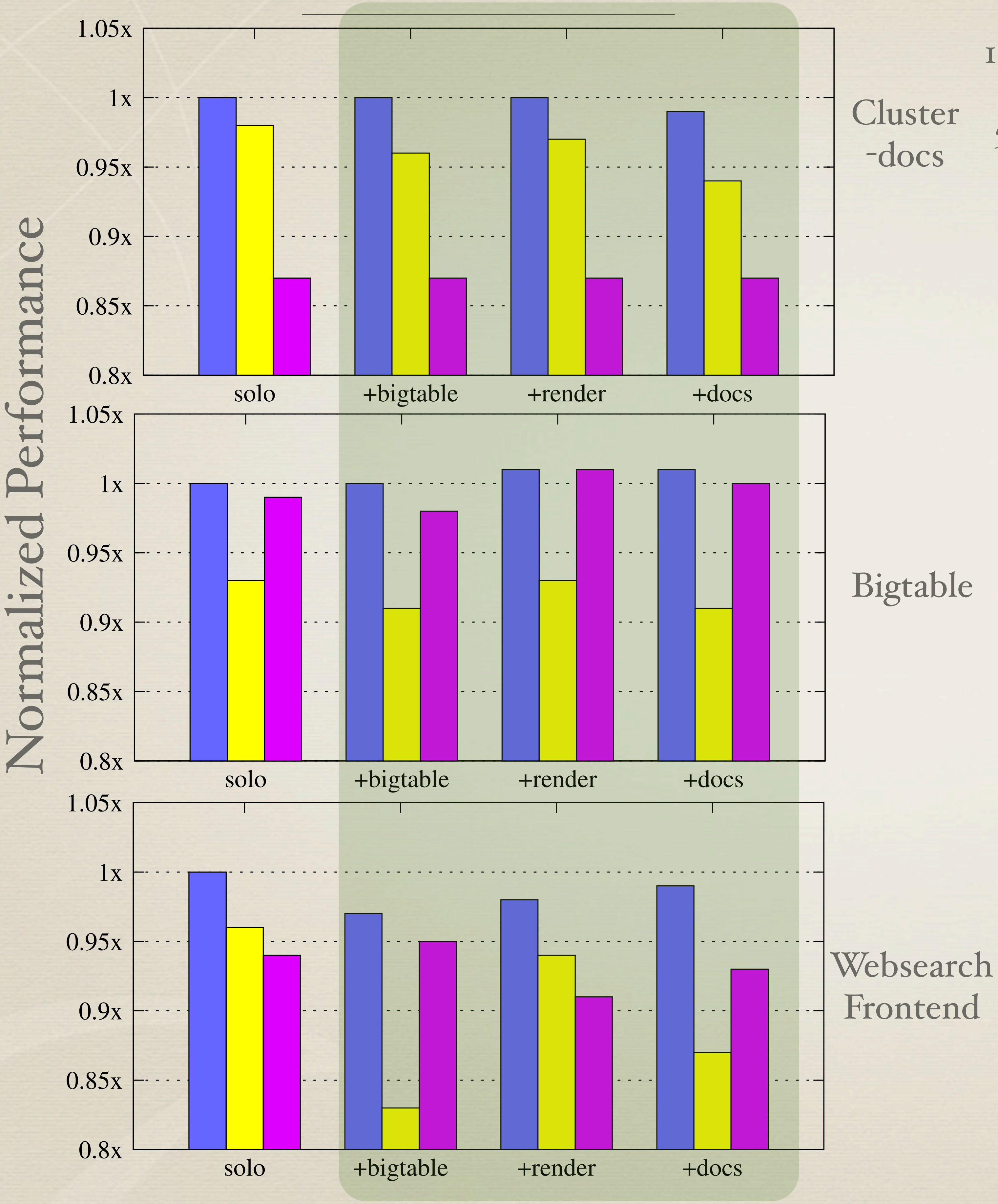
Corun



local access:

100 % 🟦 M-X X X X X X X

50 % 🟨 M-X X X X X X X

0% 🟪 M-X X X X X X X

- Solo:
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tradeoffs b/t NUMA and cache sharing/ contention

- Corun:
  - w o p c

varies for different applications and when the application's corunner changes.

Conclusion

- Combine production study and controlled study
- Production study
  - novel NUMA score
  - lightweight monitoring of large scale systems
  - careful correlation and analysis of noisy data.
  - conclusion: performance impact of NUMA is significant for large scale web-service applications
- Controlled study
  - Conclusion: some running scenarios with more remote memory accesses may outperform scenarios with more local accesses
  - This tradeoff b/t NUMA and cache sharing/contention varies for different applications and when the application's corunner changes.

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- 1% performance improvement means millions
- Failure to tease out individual micro-architectural properties -> difficult to quantify the performance impact and potential optimization benefit
- Leave performance opportunity on the table