Characterizing Storage Workloads with Counter Stacks

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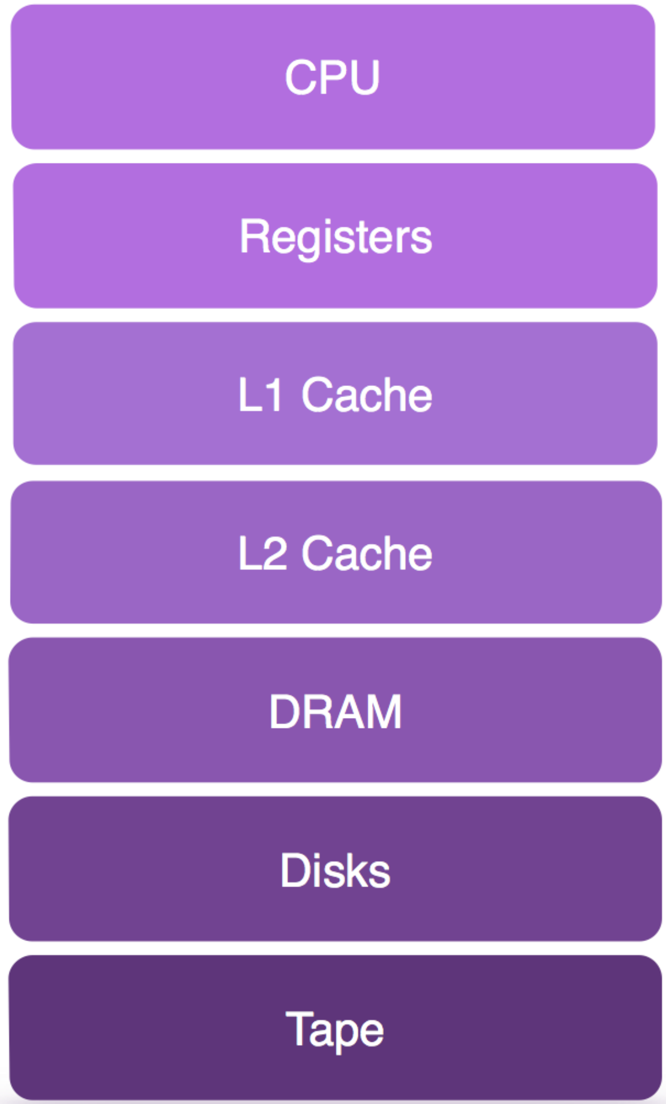
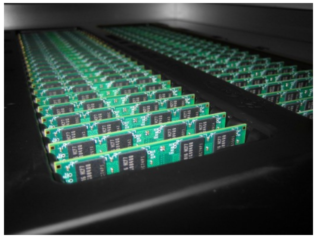
Coho Data, UBC

Memory Hierarchies

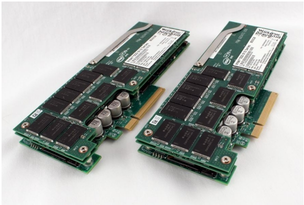


Memory Hierarchies

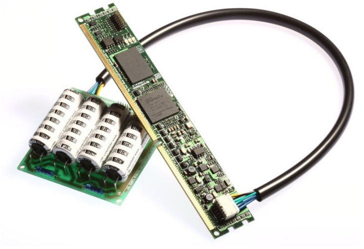
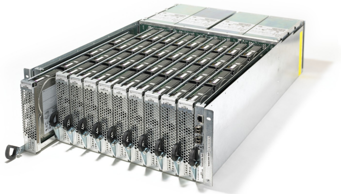
Challenge: Provisioning

512 GB DRAM + 8 TB SATA SSDs = $4,200 8.5 TB 10K – Millions IOPS

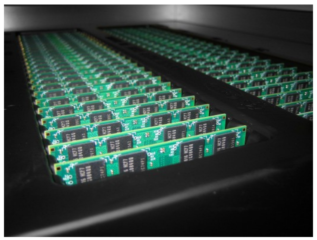
 

1.6 TB PCIe Flash + 12 TB HDDs = $12,000 13.6 TB 2.4K – 2M IOPS

8 GB NVDIMM + 60 TB JBOD = $8,000 60 TB 12K – Millions IOPS

Challenge: Provisioning




512 GB DRAM + [illegible] SATA S[illegible]Ds = $4,20[illegible] [illegible]B 10K – Millions IOPS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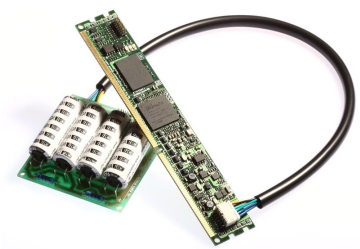
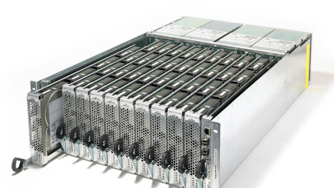
???

8 GB NVDIMM + 60 TB JBOD = $8,000 60 TB 12K – Millions IOPS

Challenge: Placement

Workload Characterization

- Provisioning and placement are difficult problems
- **What are the key workload characteristics we can use to solve these problems?**

Optimal

MIN (Belady, '66): prioritize pages with shortest *forward distance*

Practical

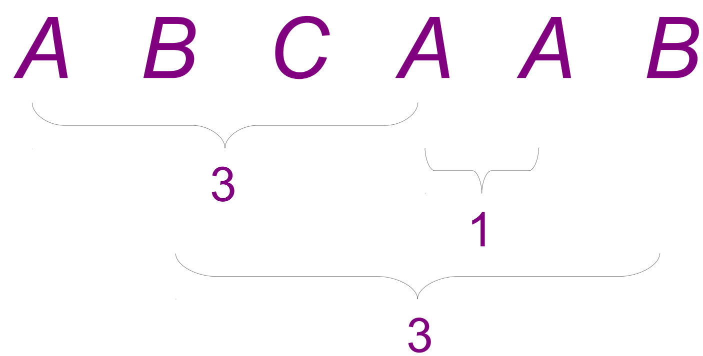
LRU: prioritize pages with shortest *reuse distance*

Practical

LRU: prioritize pages with shortest *reuse distance*

Reuse Distances

- # of distinct symbols since previous reference

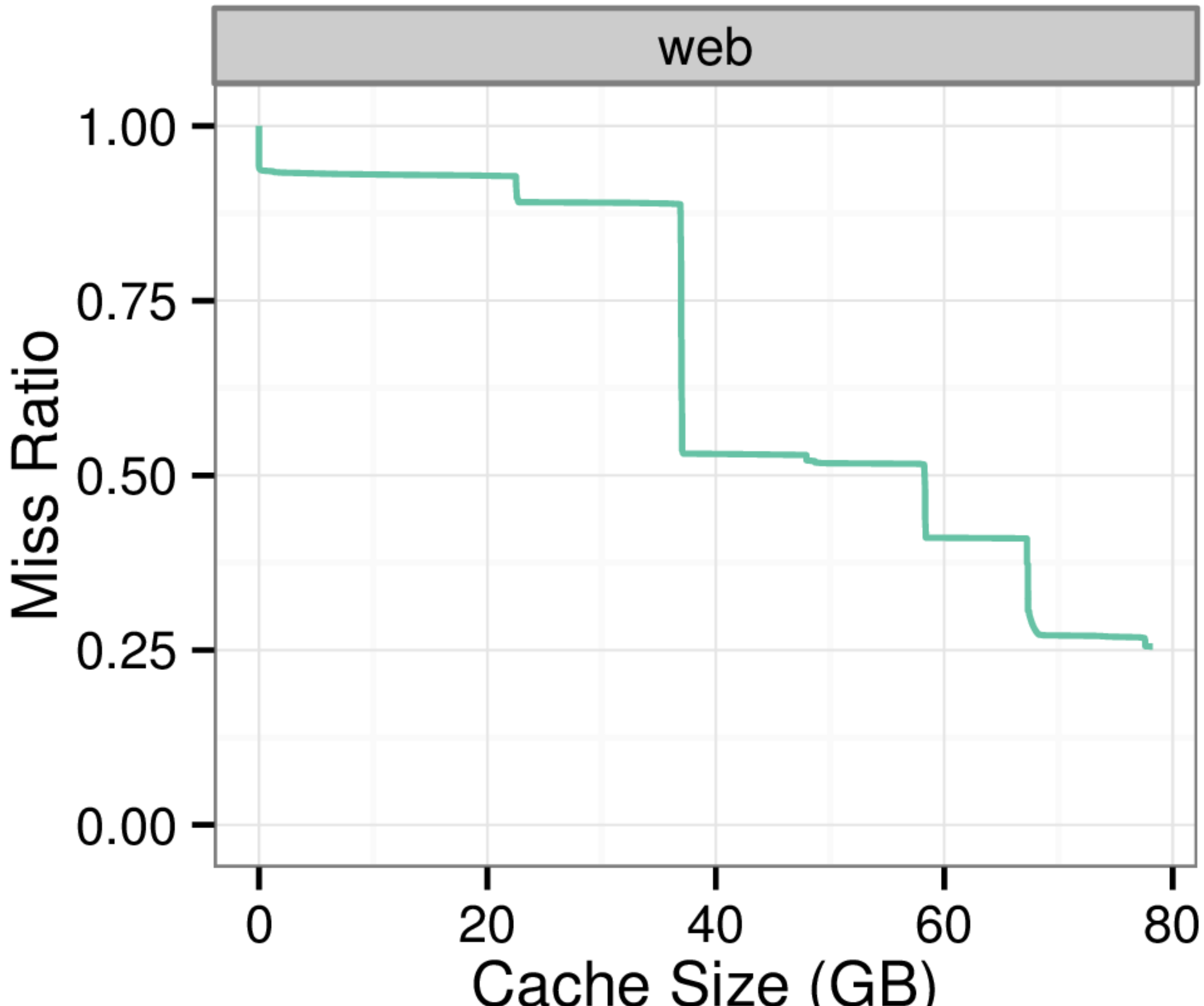


- Measure of workload locality
- Model of memory behavior

Miss Ratio Curves

- A plot of miss rate vs. cache size for a given workload under a given replacement policy
  - With LRU, this is the distribution of reuse distances

Miss Ratio Curves



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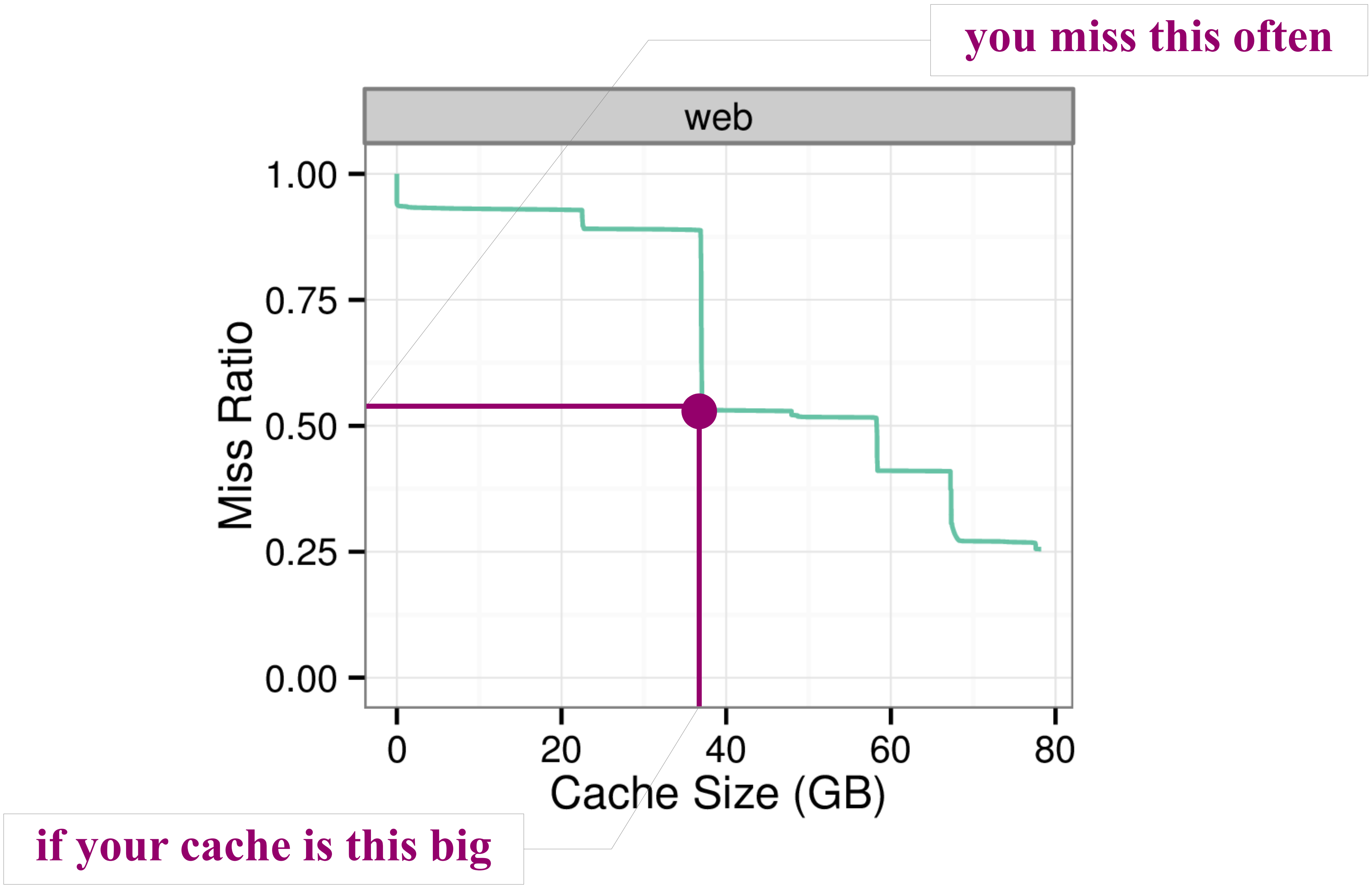

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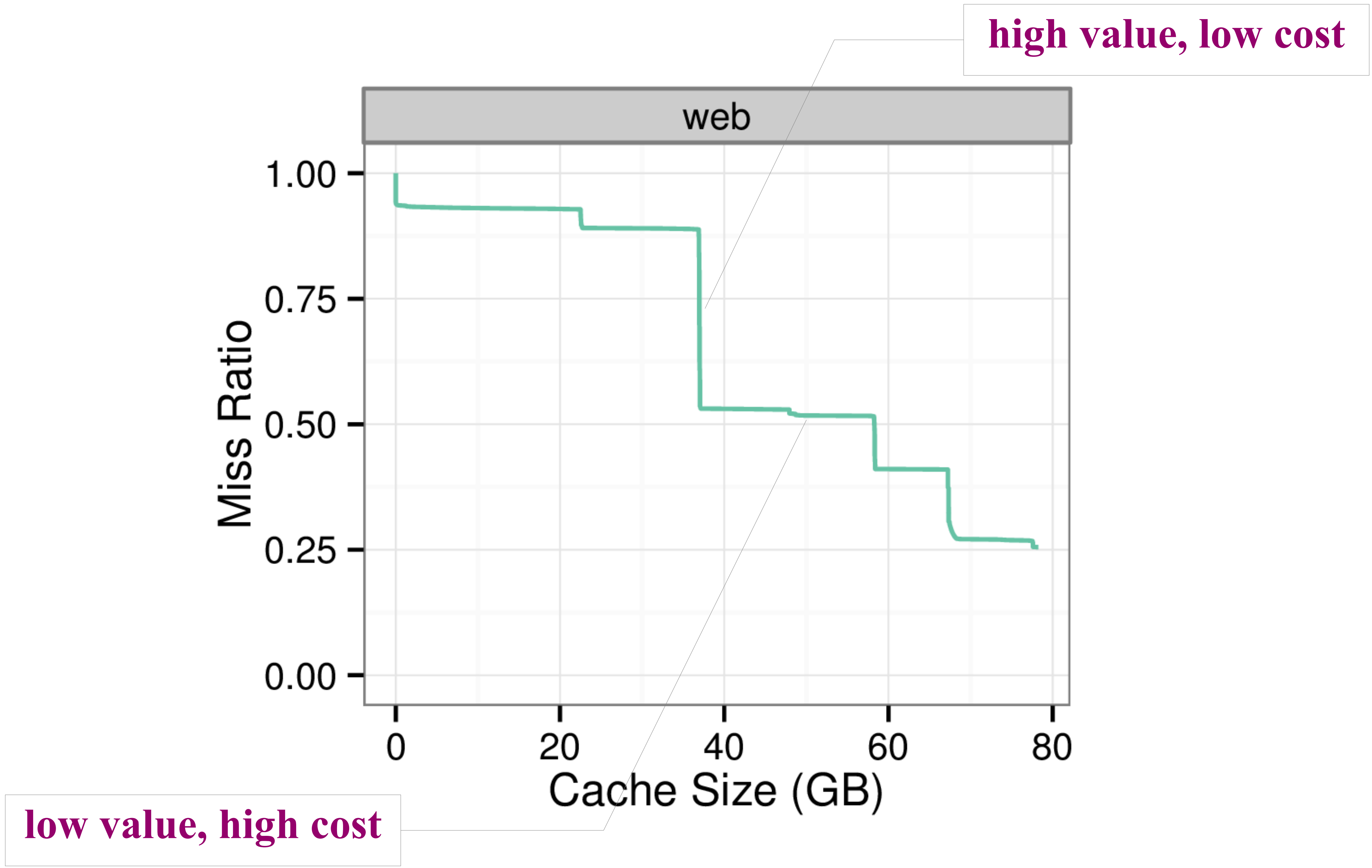

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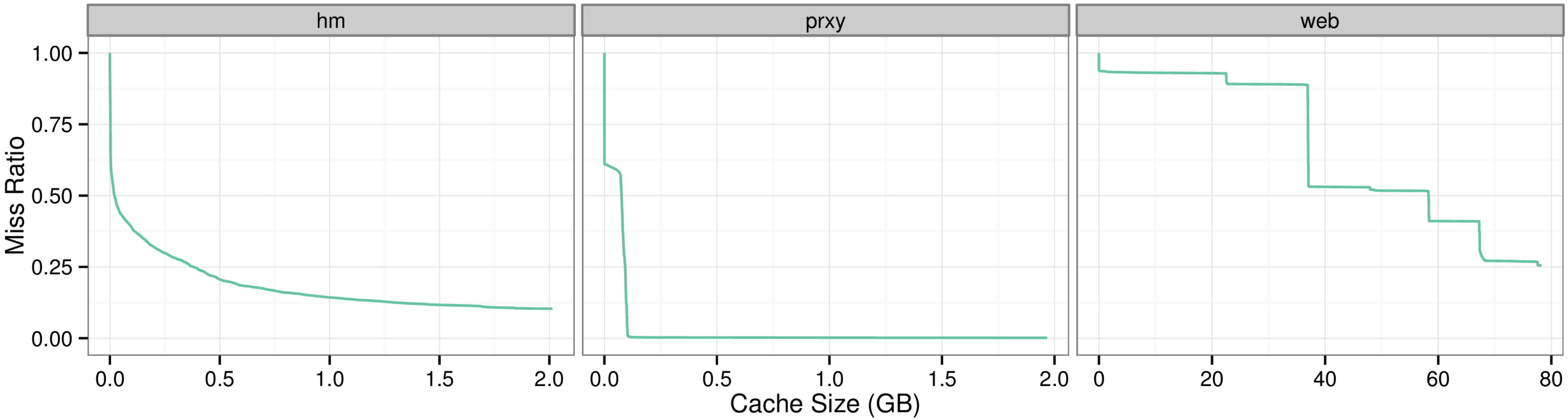
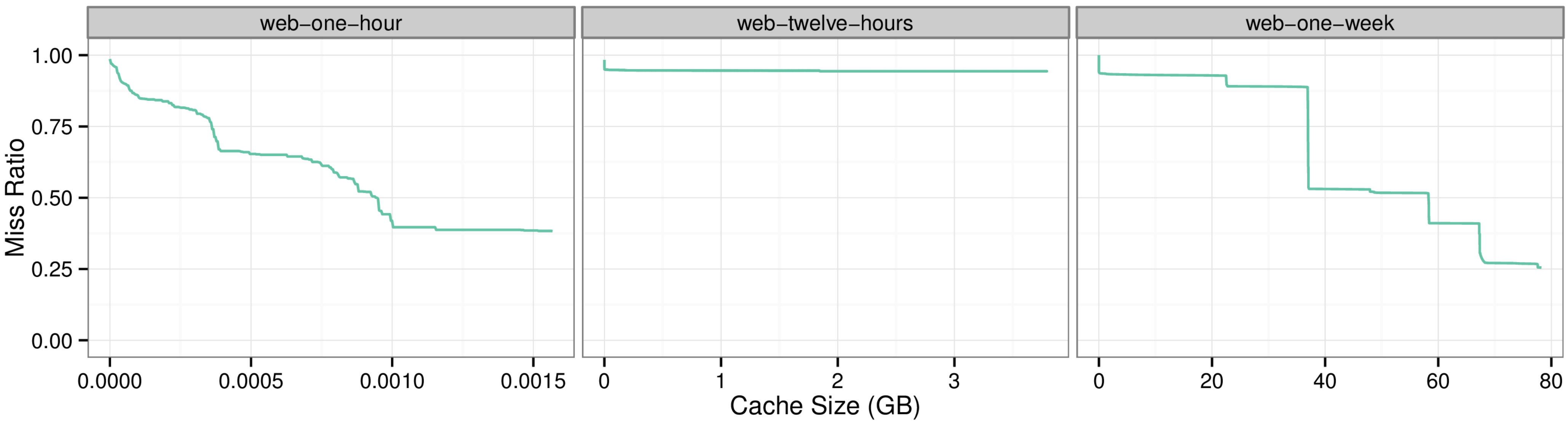


Hardware Monitor

Web Proxy

Web/SQL Server

Miss Ratio Curves



One Hour Twelve Hours One Week

Computing MRCs

- Naïve approach
  - Simulate workload once at each cache size

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Computing MRCs

- Mattson's Stack Algorithm ('70)
  - Some replacement policies are *inclusive*
    - Larger caches always include contents of smaller caches

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- Mattson's Stack Algorithm ('70)
  - Some replacement policies are *inclusive*
    - Larger caches always include contents of smaller caches
  - LRU, LFU, MIN, ...
  - For such policies, simulate all cache sizes in one pass
    - Hits at size N are hits at all M > N

Stack Algorithm for LRU

- To compute miss ratio curves for LRU:
  - Compute reuse distance of each request
  - Aggregate distances in a histogram
  - Compute the cumulative sum (CDF)

Stack Algorithm for LRU

- Complexity (N records, M unique symbols):
  - Time: O(N * M)
    - Reduced to O(N * log(N)) (Bennett et al., '75)
    - Reduced to O(N * log(M)) (Almási et al., '02)
  - Space: O(M)

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Still Not Practical

- 92 GB RAM to compute MRC of 3 TB workload

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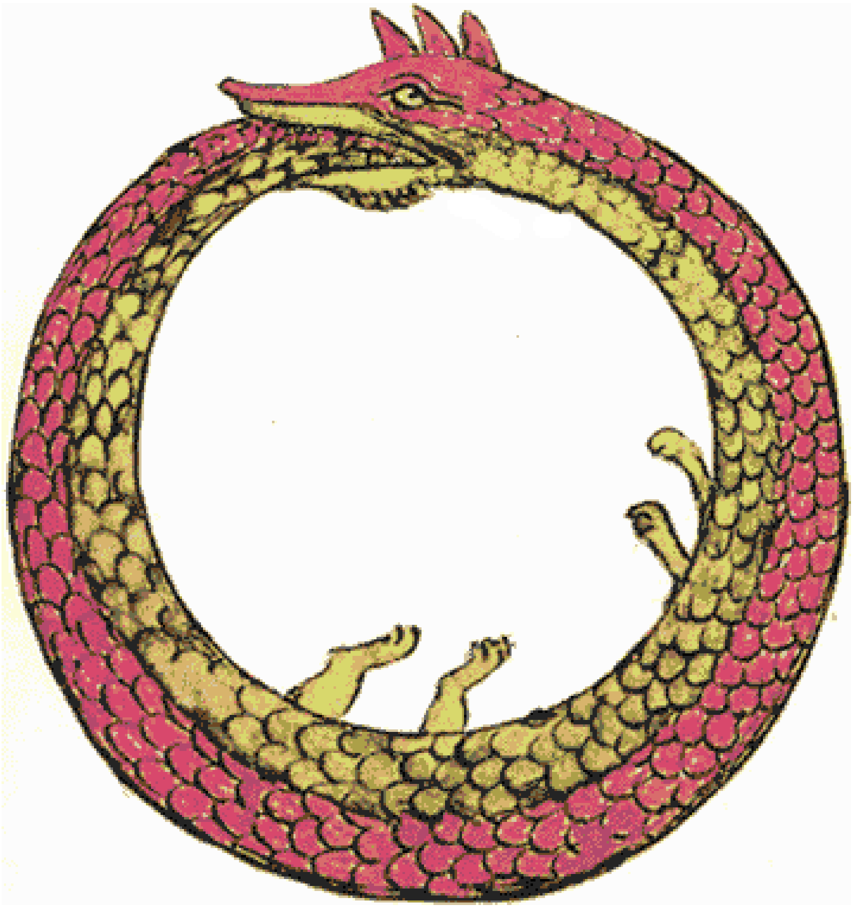

Stack Algorithm for LRU

- To compute miss ratio curves for LRU:
  - **Compute reuse distance of each request**
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- **Can we do this more efficiently?**

Stack Algorithm for LRU

- To compute miss ratio curves for LRU:
  - **Compute reuse distance of each request**
  - Aggregate distances in a histogram
  - Compute the cumulative sum (CDF)

- **Can we do this more efficiently? Yes.**
  - **80 MB for approximate MRC of 3 TB workload**

Counter Stacks

- *Measure uniqueness over time*

- Observation: computing reuse distances is related to counting distinct elements

- Consider a 'stack' of cardinality counters, one for each request

Calculating with Counts

Reference String: A

Calculating with Counts

Reference String:	A
cardinality counter started at t_0	1

Calculating with Counts

Reference String: *A* B

cardinality counter started at t_0	1

Calculating with Counts

Reference String:	*A*	B
cardinality counter started at t_0	1	2

Calculating with Counts

Reference String:	*A*	B
cardinality counter started at t_0	1	2
cardinality counter started at t_1		1

Calculating with Counts

Reference String:	*A*	*B*	C
cardinality counter started at t_0	1	2	
cardinality counter started at t_1		1	

Calculating with Counts

Reference String:	*A*	*B*	C
cardinality counter started at t_0	1	2	3
cardinality counter started at t_1		1	

Calculating with Counts

Reference String:	*A*	*B*	C
cardinality counter started at t_0	1	2	3
cardinality counter started at t_1		1	2

Calculating with Counts

Reference String:	*A*	*B*	C
cardinality counter started at t_0	1	2	3
cardinality counter started at t_1		1	2
cardinality counter started at t_2			1

Calculating with Counts

Reference String:	*A*	*B*	*C*	A
cardinality counter started at t_0	1	2	3	
cardinality counter started at t_1		1	2	
cardinality counter started at t_2			1	

Calculating with Counts

Reference String:	*A*	*B*	*C*	A
cardinality counter started at t_0	1	2	3	3
cardinality counter started at t_1		1	2	
cardinality counter started at t_2			1	

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Reference String:	*A*	*B*	*C*	A
cardinality counter started at t_0	1	2	3	3
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cardinality counter started at t_2			1	

Calculating with Counts

Reference String:	*A*	*B*	*C*	A
cardinality counter started at t_0	1	2	3	3
cardinality counter started at t_1		1	2	3
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Calculating with Counts

Reference String:	*A*	*B*	*C*	A
cardinality counter started at t_0	1	2	3	3
cardinality counter started at t_1		1	2	3
cardinality counter started at t_2			1	2
cardinality counter started at t_3				1

Calculating with Counts

Reference String:	*A*	*B*	*C*	*A*	
cardinality counter started at t_0	1	2	3	3	+0
cardinality counter started at t_1		1	2	3	+1
cardinality counter started at t_2			1	2	
cardinality counter started at t_3				1	

Observation 1: A difference in the change between adjacent counters implies a repeated reference.

Calculating with Counts

Reference String:	*A*	*B*	*C*	*A*	
cardinality counter started at t_0	1	2	3	3	+0
cardinality counter started at t_1		1	2	3	+1
cardinality counter started at t_2			1	2	
cardinality counter started at t_3				1	

Observation 1: A difference in the change between adjacent counters implies a repeated reference.

Observation 2: The location of the difference stores the reuse distance.

Calculating with Counts

A	B	C	A
1	2	3	3
	1	2	3
		1	2
			1

Matrix C

A	B	C	A
1	1	1	0
	1	1	1
		1	1
			1

Δx

A	B	C	A
0	0	0	1
	0	0	0
		0	0
			0

Δy

Perfect Counting

- One cardinality counter per request
- Quadratic overhead!

Perfect Counting

- ~5 ZB RAM to compute MRC of 3 TB workload

Practical Counting

- $\mathbb{C}$ is highly redundant
  - Space/accuracy tradeoff

A	*B*	*C*	*A*	*A*	*C*	*A*	*B*	*C*	*A*
1	2	3	3	3	3	3	3	3	3
	1	2	3	3	3	3	3	3	3
		1	2	2	2	2	3	3	3
			1	1	2	2	3	3	3
				1	2	2	3	3	3
					1	2	3	3	3
						1	2	3	3
							1	2	3
								1	2
									1

Practical Counting

- *Downsample*

A	B	C	A	A	C	A	B	C	A
1	2	3	3	3	3	3	3	3	3
	1	2	3	3	3	3	3	3	3
		1	2	2	2	2	3	3	3
			1	1	2	2	3	3	3
				1	2	2	3	3	3
					1	2	3	3	3
						1	2	3	3
							1	2	3
								1	2
									1

Practical Counting

- *Downsample*
  - Only output every k^{th} counter

A	*B*	*C*	*A*	*A*	*C*	*A*	*B*	*C*	*A*
1	2	3	3	3	3	3	3	3	3
	1	2	3	3	3	3	3	3	3
		1	2	2	2	2	3	3	3
			1	1	2	2	3	3	3
				1	2	2	3	3	3
					1	2	3	3	3
						1	2	3	3
							1	2	3
								1	2
									1

Practical Counting

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A	*B*	*C*	*A*	*A*	*C*	*A*	*B*	*C*	*A*
1	2	3	3	3	3	3	3	3	3
	1	2	3	3	3	3	3	3	3
		1	2	2	2	2	3	3	3
			1	1	2	2	3	3	3
				1	2	2	3	3	3
					1	2	3	3	3
						1	2	3	3
							1	2	3
								1	2
									1

Practical Counting

- *Prune*: discard counters with similar values (i.e., differing less than pruning distance *p)*

A	B	C	A	A	C	A	B	C	A
1	2	3	3	3	3	3	3	3	3
	1	2	3	3	3	3	3	3	3
		1	2	2	2	2	3	3	3
			1	1	2	2	3	3	3
				1	2	2	3	3	3
					1	2	3	3	3
						1	2	3	3
							1	2	3
								1	2
									1

Practical Counting

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A	B	C	A	A	C	A	B	C	A
1	2	3	3	3	3	3	3	3	3
	1	2	3	3	3	3	3	3	3
		1	2	2	2	2	3	3	3
			1	1	2	2	3	3	3
				1	2	2	3	3	3
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									1

Approximate Counting

- *Estimate*: use probabilistic counters

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- *Estimate*: use probabilistic counters
  - HyperLogLog (Flajolet et al., '07)
  - Accurate estimates of large multisets with sublinear space

Counter Stacks

- Sublinear memory overhead
  - Practical for online computation

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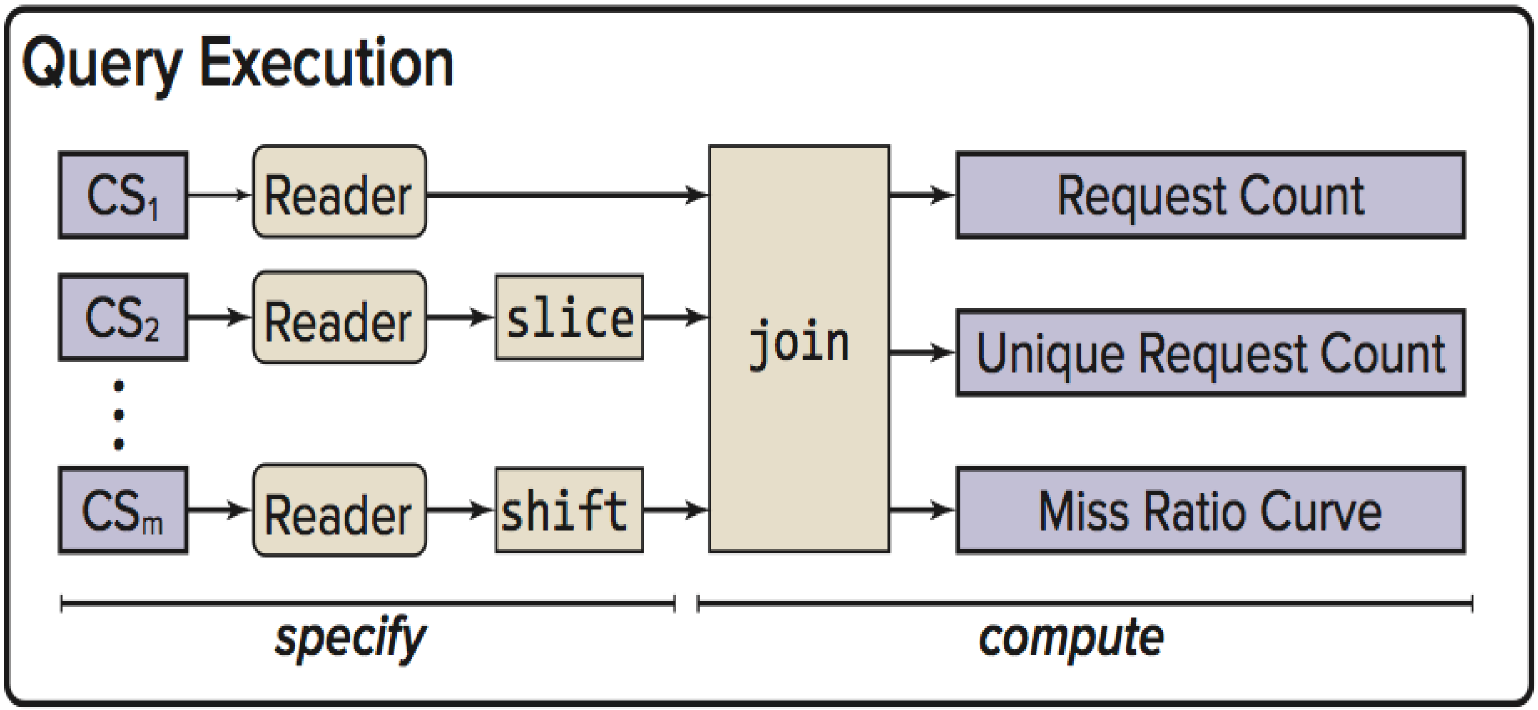
  - Practical for online computation

- But wait, there's more...

Counter Stack Streams

- We can compute Δx, Δy, and reuse distances with only the last two columns of C
- We store all columns on disk as a **Counter Stack Stream**
  - Preserves a *history of locality*

Counter Stack Stream Queries



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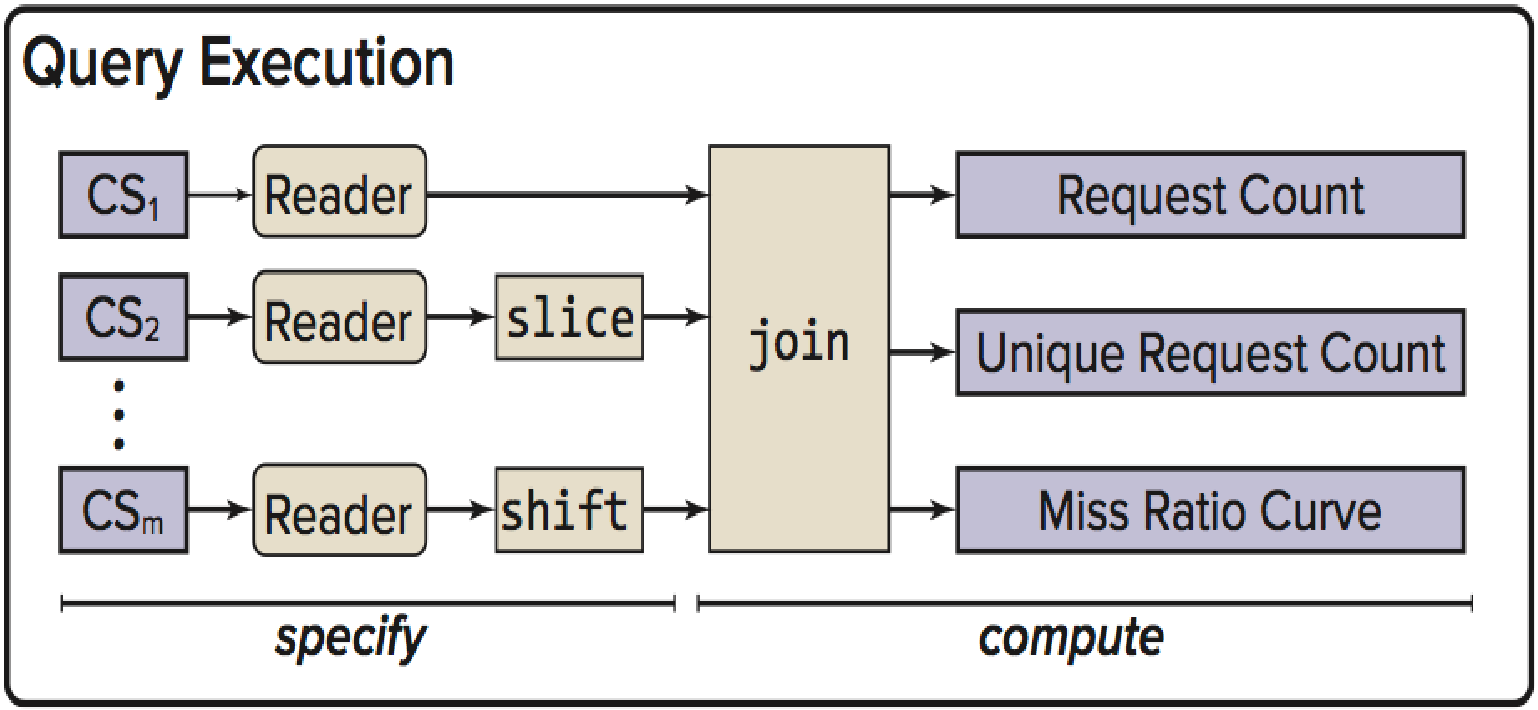

- Search for outliers
- Identify phase changes
- Explore coarse-grain scheduling

How Much Do They Cost?

- MSR Cambridge storage traces
  - 2.7 TB unique data
  - 13 servers, 36 volumes, one week
  - 417 million records in 5 GB of gzipped CSV

Technique	RAM	Throughput	Storage
Mattson	92 GB	680 K reqs/sec	2.9 GB
high-fidelity CS	80.6 MB (1168x)	2.29 M reqs/sec (3.37x)	11 MB (270x)
low-fidelity CS	78.5 MB (1200x)	2.31 M reqs/sec (3.40x)	747 KB (4070x)

compression parameters are tunable:
high: $k = 10^6$, $p = 98\%$ low: $k = 10^6$, $p = 90\%$

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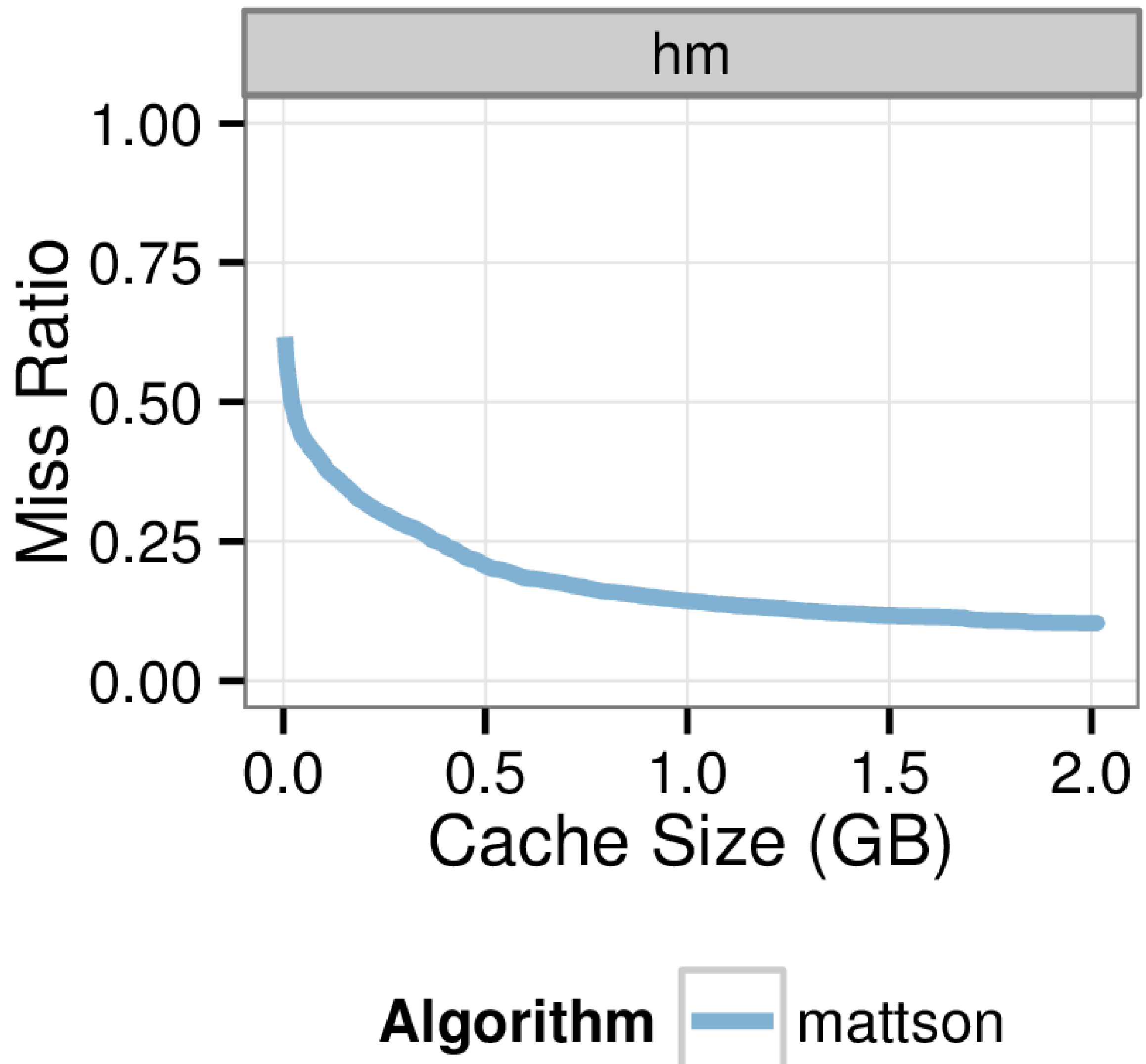

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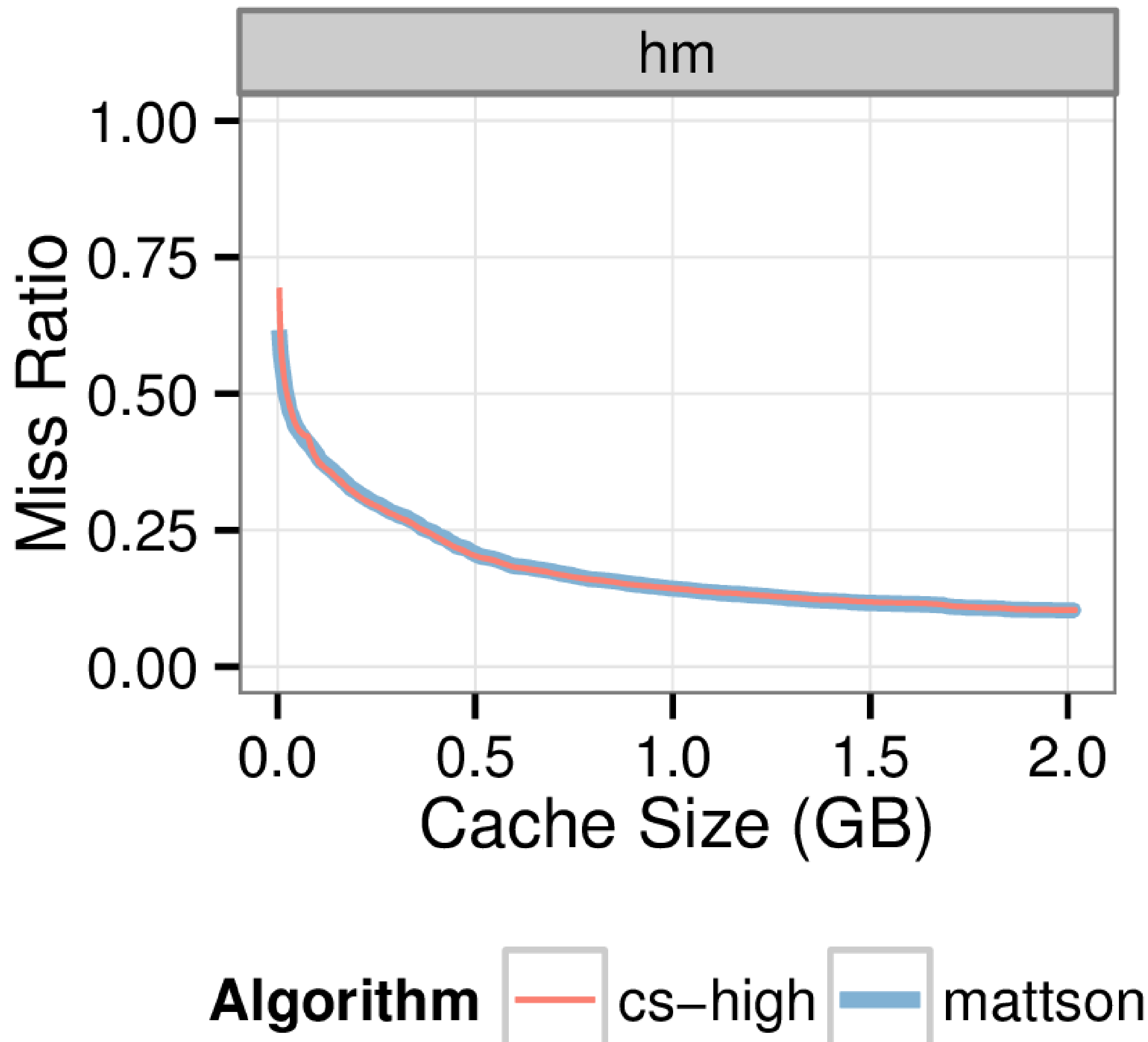

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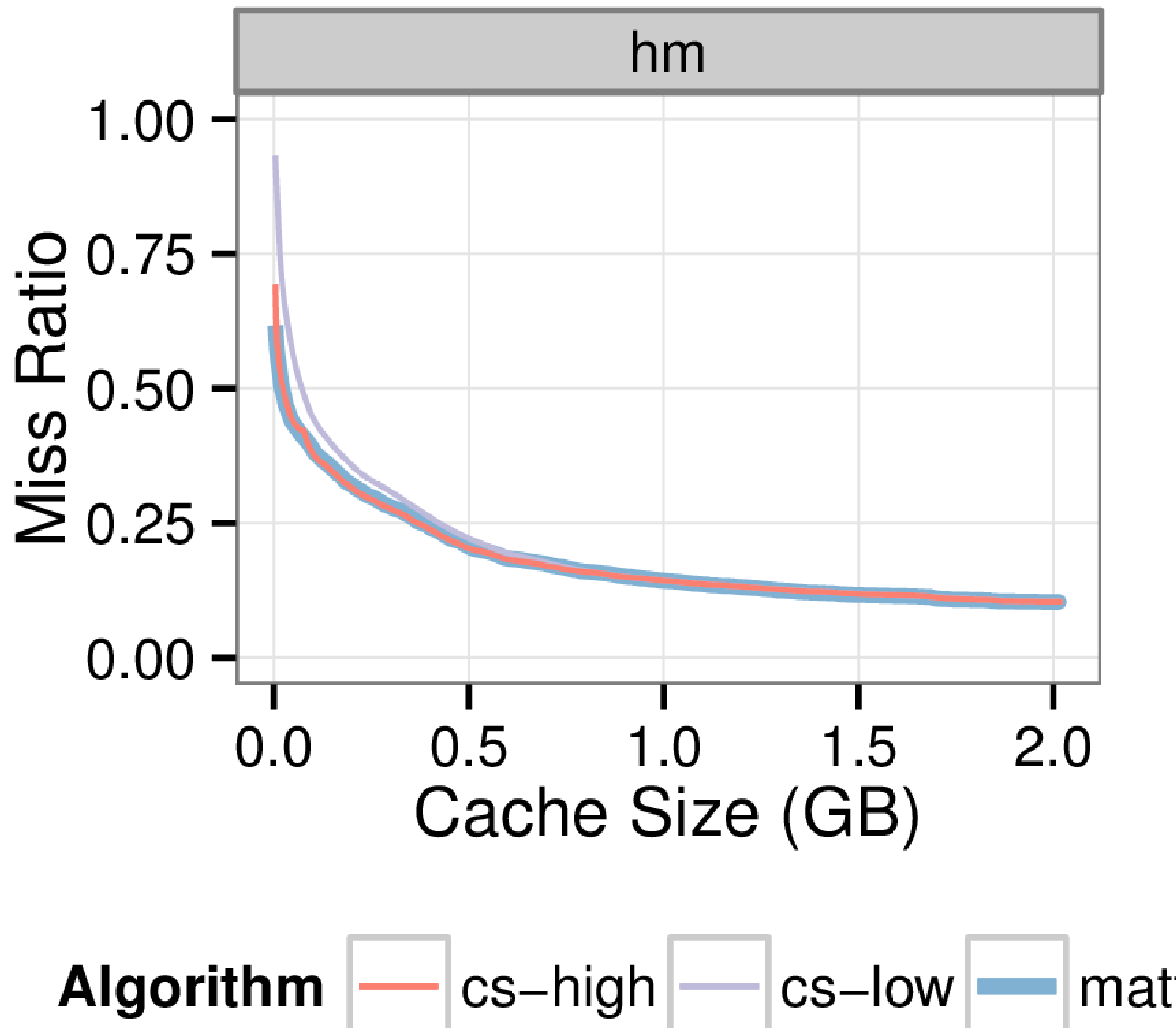

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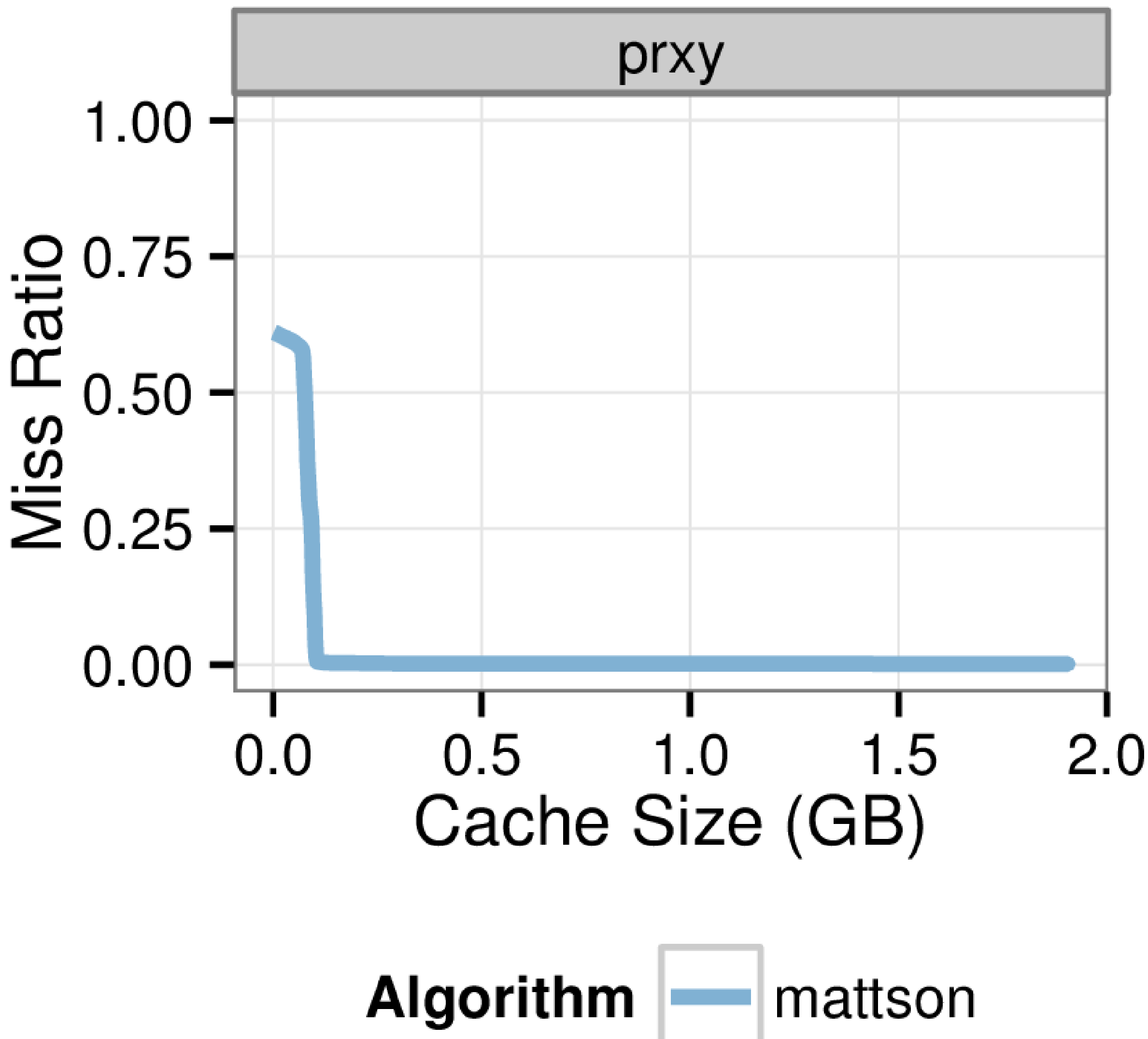

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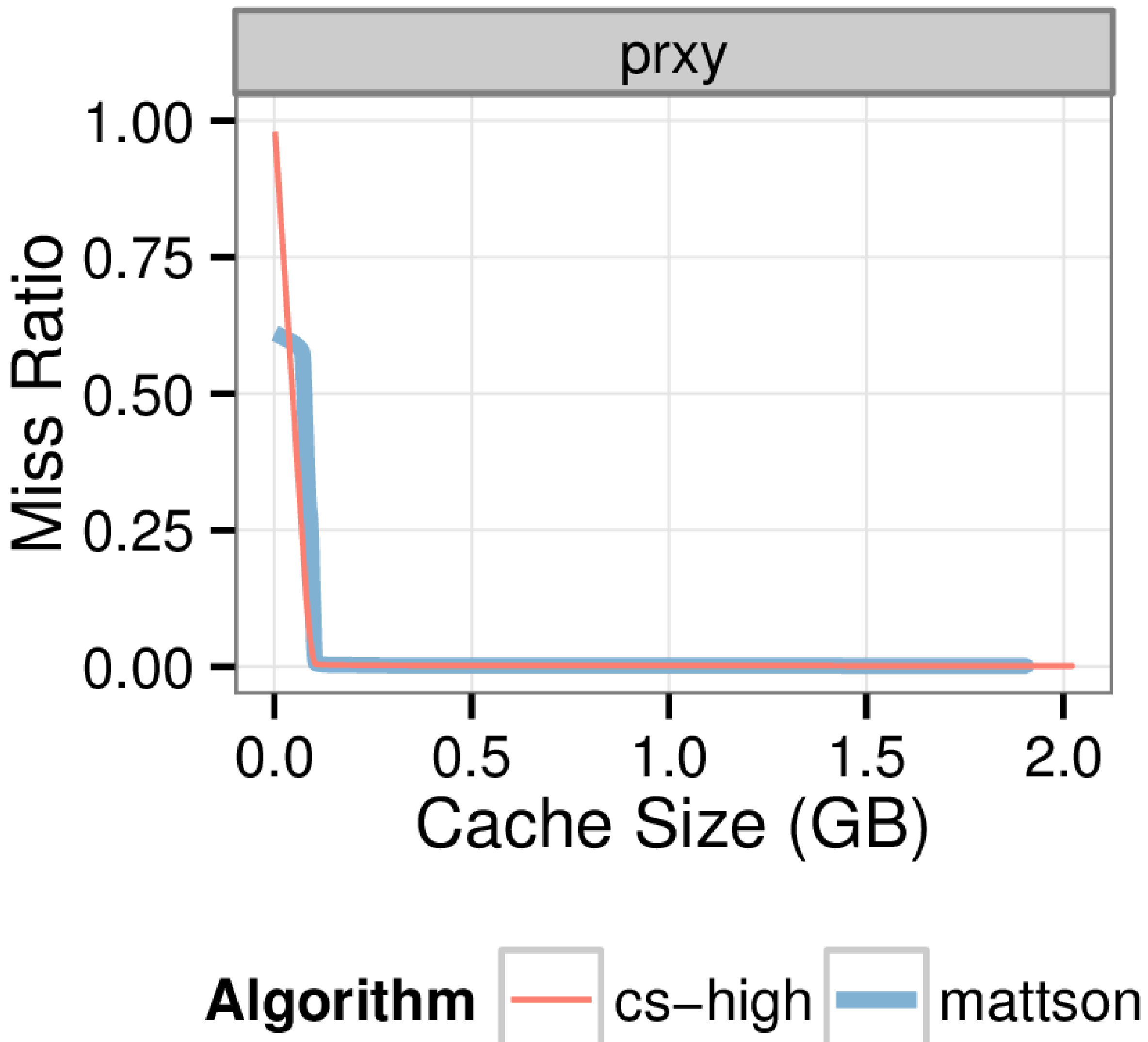

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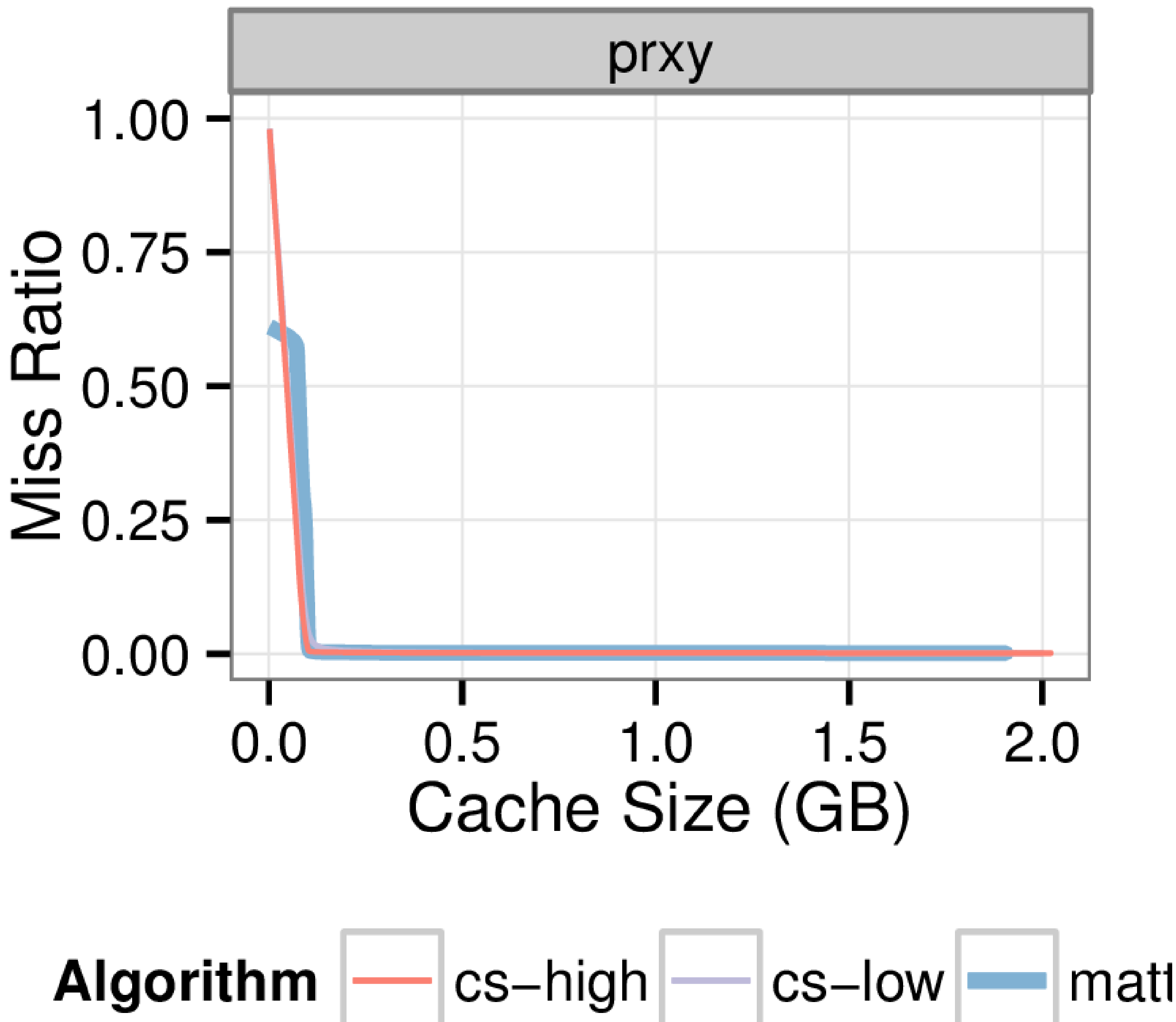

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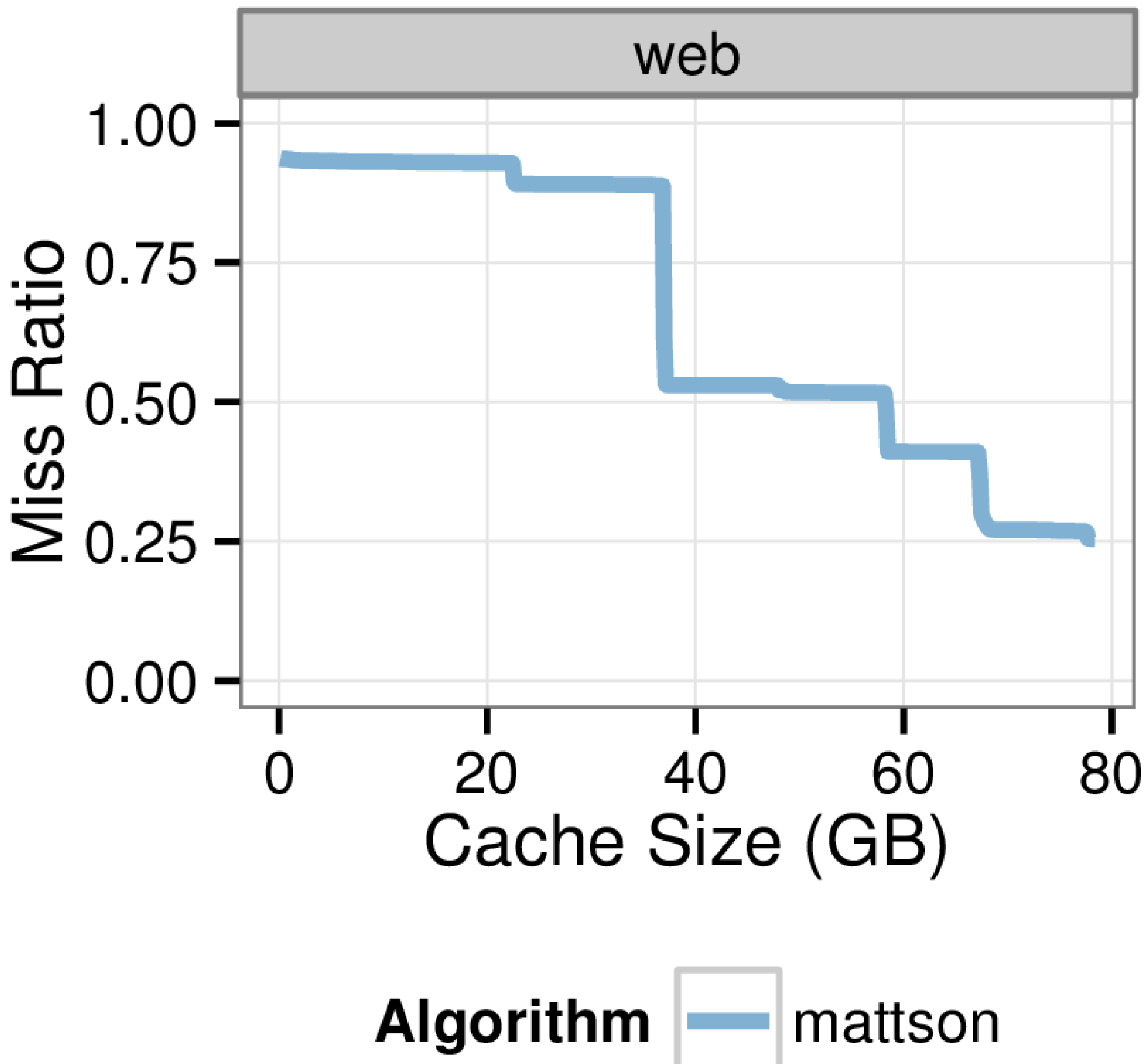

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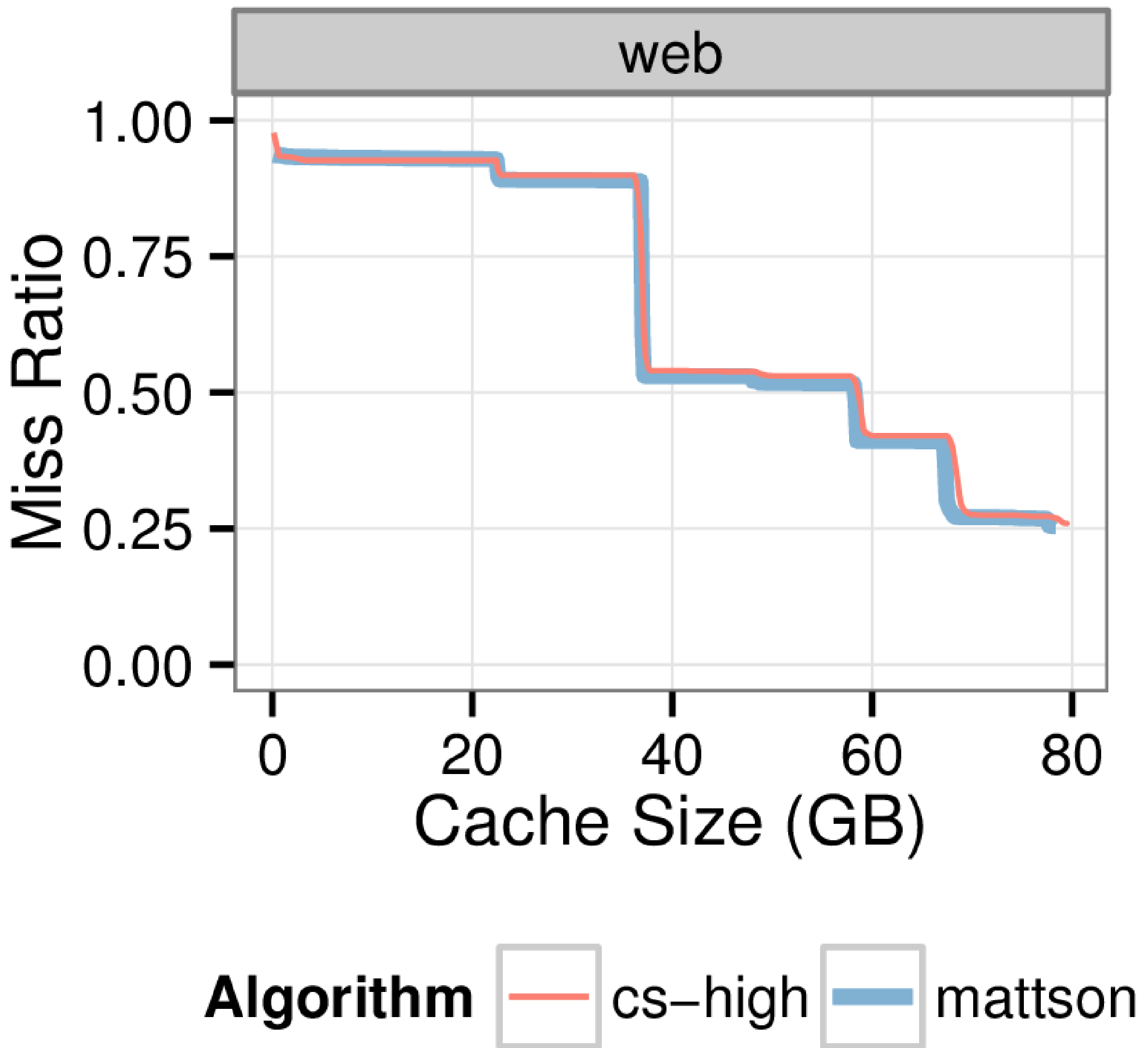

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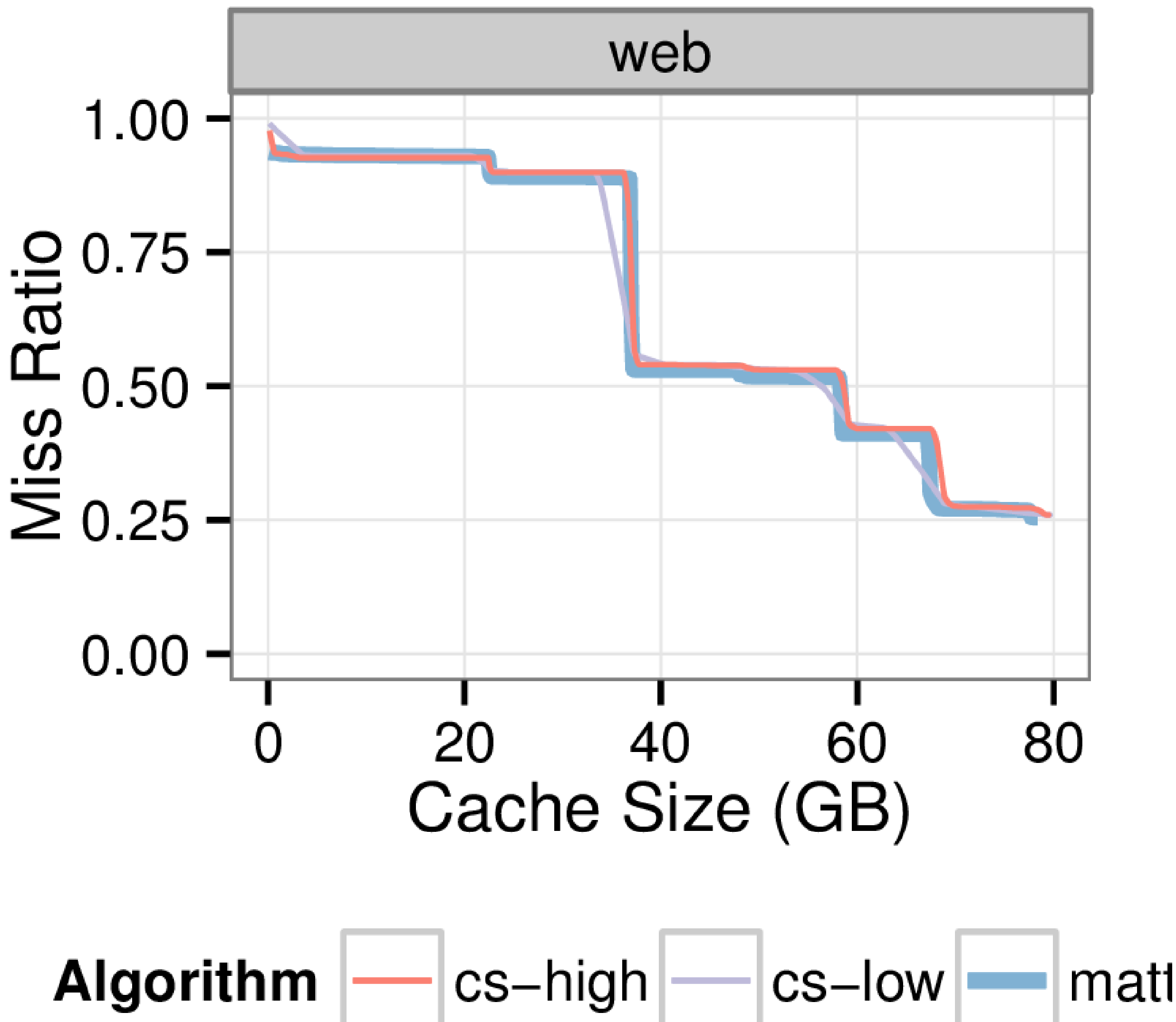

Conclusions

- Managing data can be data-intensive!
- Counter Stacks measure uniqueness over time
  - Low memory and storage overheads
  - Easy to capture, process, and store workload histories
- Used in production:
  - Collecting traces from the field
  - Making online placement decisions
  - Forecasting benefits of adding more hardware

Thanks!

Questions?

How Well Do They Work?