# Addressing Shared Resource Contention in Multicore Processors via Scheduling

ASPLOS'10 by Sergey Zhuravlev, et al.

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# Problem Statement

- Multicore processors were prevalent (2010)
  - Even truer today
  - Opportunity for thread level parallelism
- Scheduling among multiple cores is hard
  - Simply keep cores busy is not good enough
  - Apps may compete for shared resource (e.g. cache)

What is the best scheduling approach to deal with resource contention?

# Scheduling Does Matter

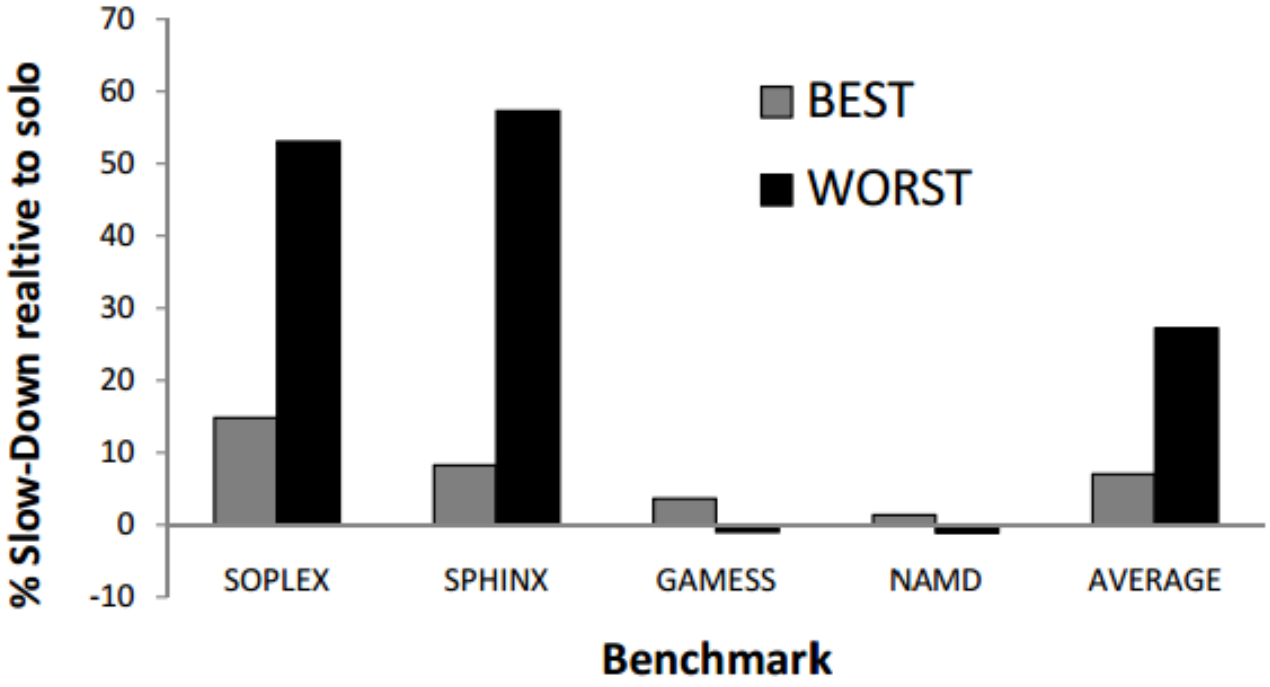
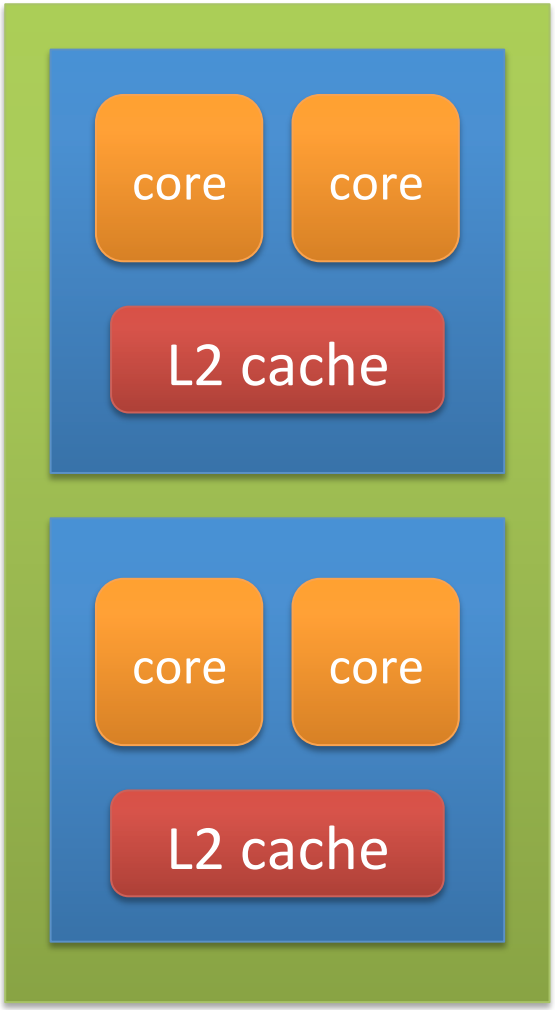



**Figure 1.** The performance degradation relative to running solo for two different schedules of SPEC CPU2006 applications on an Intel Xeon X3565 quad-core processor (two cores share an LLC).



# Why Worse Than Solo?

- Thought experiment:
  - Two apps: A: low miss rate, B: high miss rate
  - Who will suffer more when sharing cache with another application C?
  - Cache attention: C brings its own data to cache

Answer 1:
A, because B already has very high miss rate anyway.
Assumption is cache attention is the main cause of performance degradation.

Answer 2:
B, because the miss penalty is larger
Assumption is cache attention is NOT the main cause of performance degradation.

# Outline: Cache-aware Scheduling

- Classification scheme
  - Classification scheme is the information you use to make a decision
  - **How** can we study classification scheme alone?

- Classification scheme + Scheduling policy
  - Scheduling policy is how you use the information

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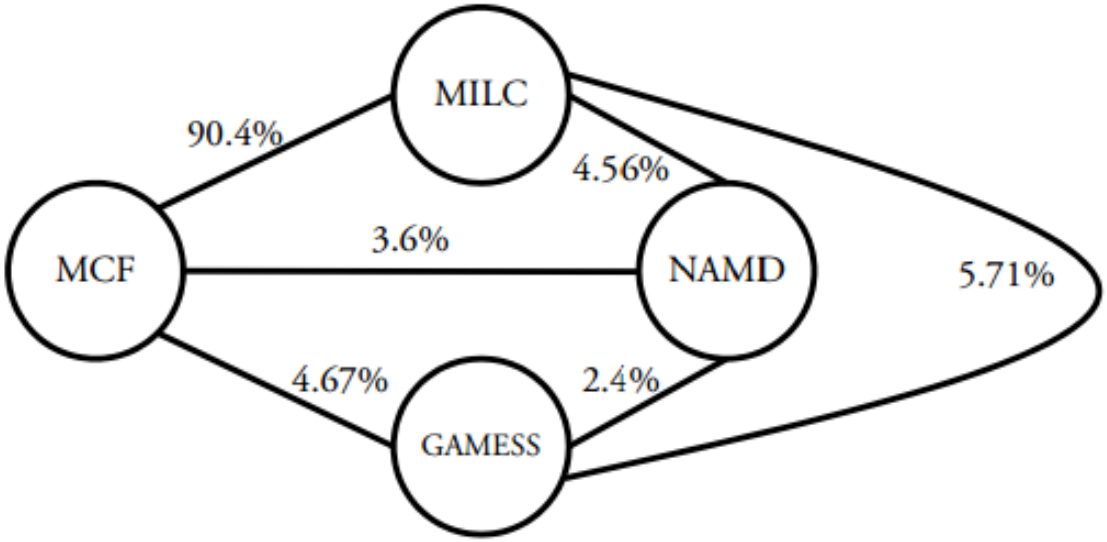
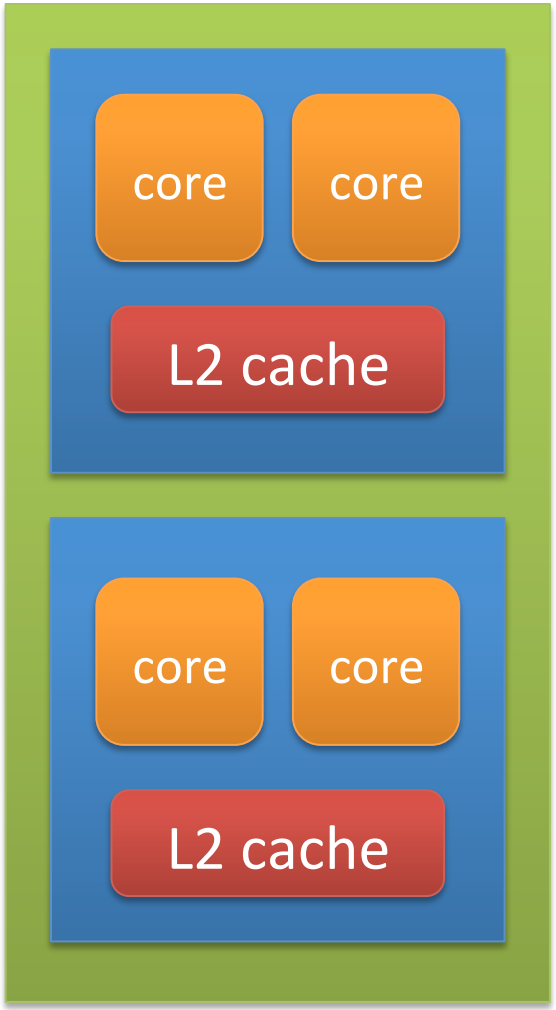
# Study Classification Scheme Alone

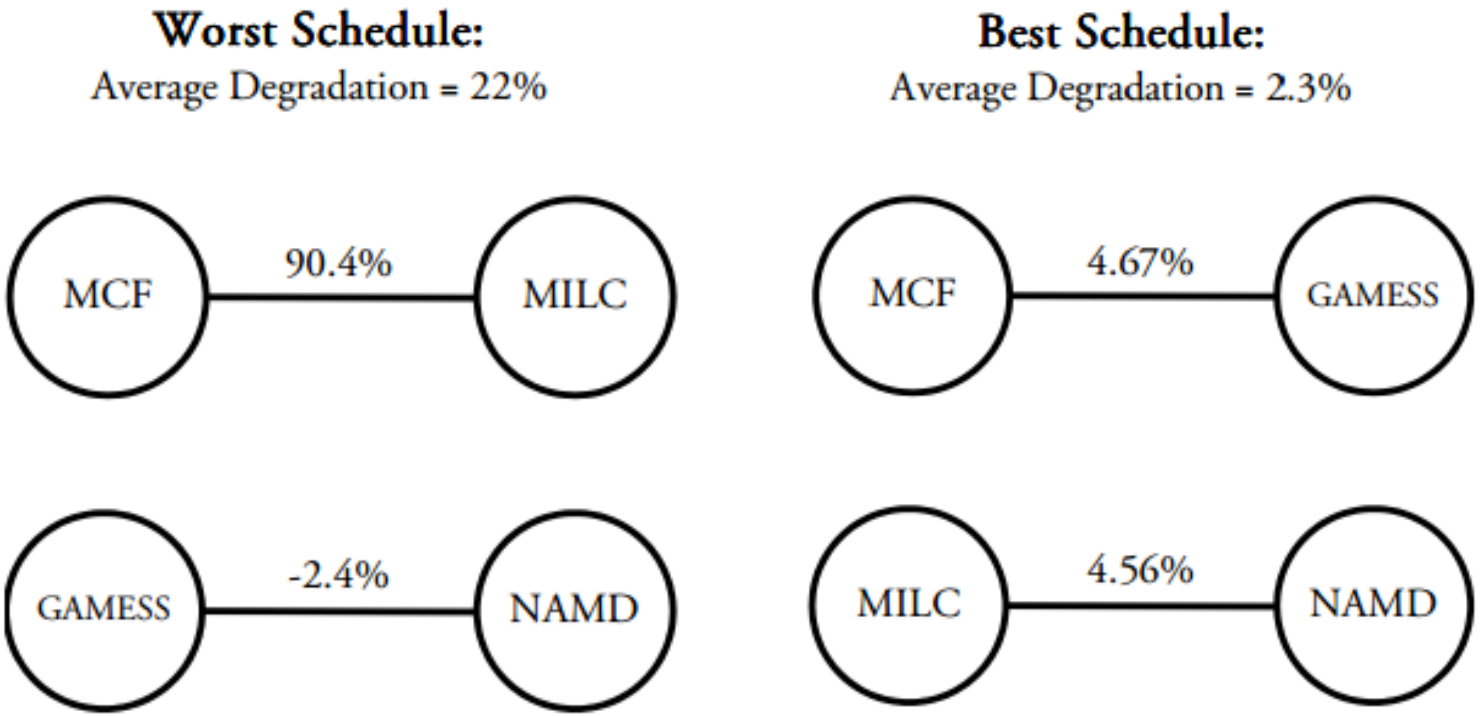
- Perfect scheduling policy



# Study Classification Scheme Alone

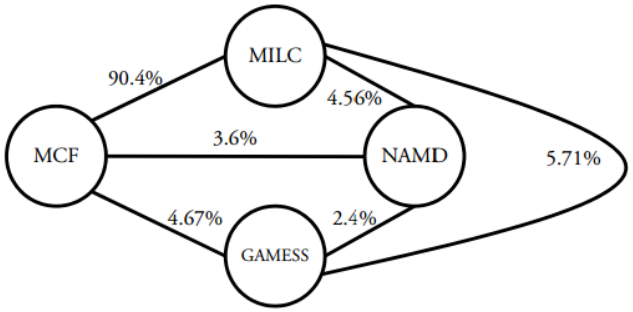
- Perfect scheduling policy



# Evaluating Classification Scheme

- Optimal Schedule (OS)
  - Optimal classification scheme +

    Perfect scheduling policy



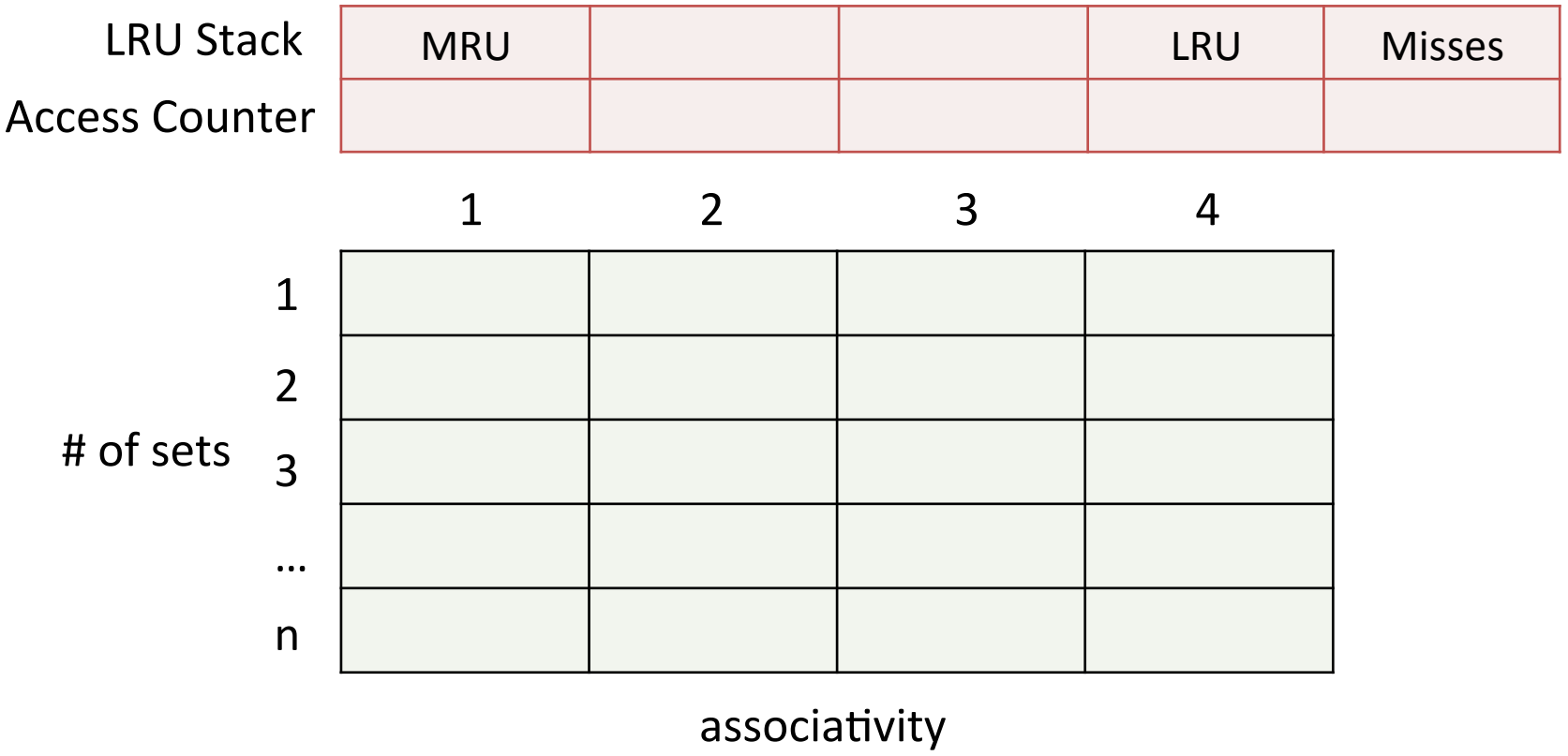

- Estimated Best Schedule (EBS)
  - Classification scheme under evaluation +

    Perfect scheduling policy
- Degradation due to classification scheme

$$Relative\ Degradation = \frac{Degradation\ of\ EBS - Degradation\ of\ OS}{Degradation\ of\ OS}$$

# Collecting Cache Performance data

- Stack Distance Profile



# Classification Schemes - SDC

- Key Idea
  - Model how two application threads compete for the LRU stack positions

# Classification Schemes – Animal Classes

- 4 classes of application threads (classified based on stack distance profiles)
  - Turtle: low use of the shared cache
  - Sheep: low miss rate, insensitive to # of cache ways
  - Rabbit: low miss rate, sensitive to # of cache ways
  - Devil: high miss rate, tends to thrash the cache

Relative Performance Degradation Table

| | Turtle | Sheep | Rabbit | Devil |
|---|---|---|---|---|
| Turtle | 0 | | | |
| Sheep | | | | |
| Rabbit | | | | |
| Devil | | | | 8 |

# Classification Schemes – Miss Rate

- Simply use “miss rate” as heuristics
  - Identify high miss rate application threads and separate them into different caches
  - Why?
    - exclusive cache lowers miss rate
    - exclusive prefetching HW and lowly-contended front-side bus reduces miss penalty

# Classification Schemes - Pain

- Cache Sensitivity
  - How much an application will suffer due to cache contention

$$S = \left(\frac{1}{1+n}\right) \sum_{i=0}^{n} i * h(i)$$

- Cache Intensity
  - How aggressively an application thread uses cache

$$Z = \#\ cache\ accesses\ per\ one\ million\ instructions$$

- Pain of Co-Schedule

$$Pain(A_B) = S(A) \times Z(B)$$

$$Pain(A, B) = Pain(A_B) + Pain(B_A)$$

# Comparing Classification Schemes

- Workload: 10 benchmarks from SPEC2006 Suite

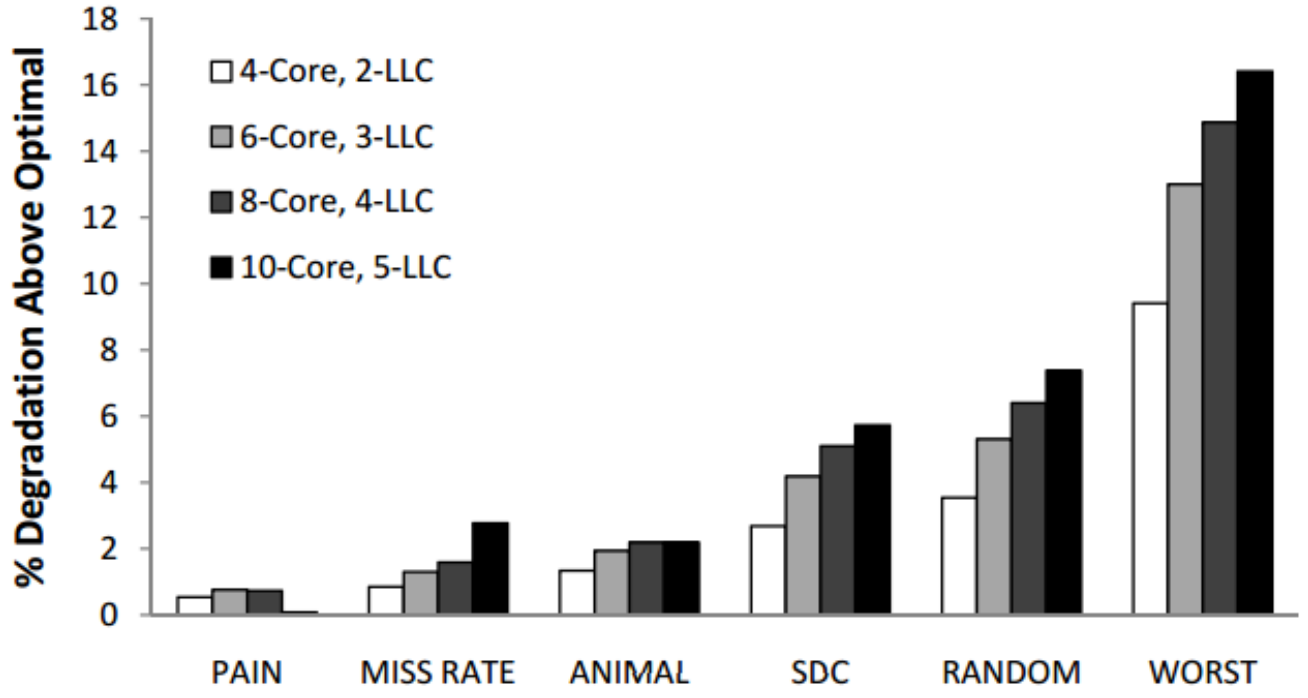
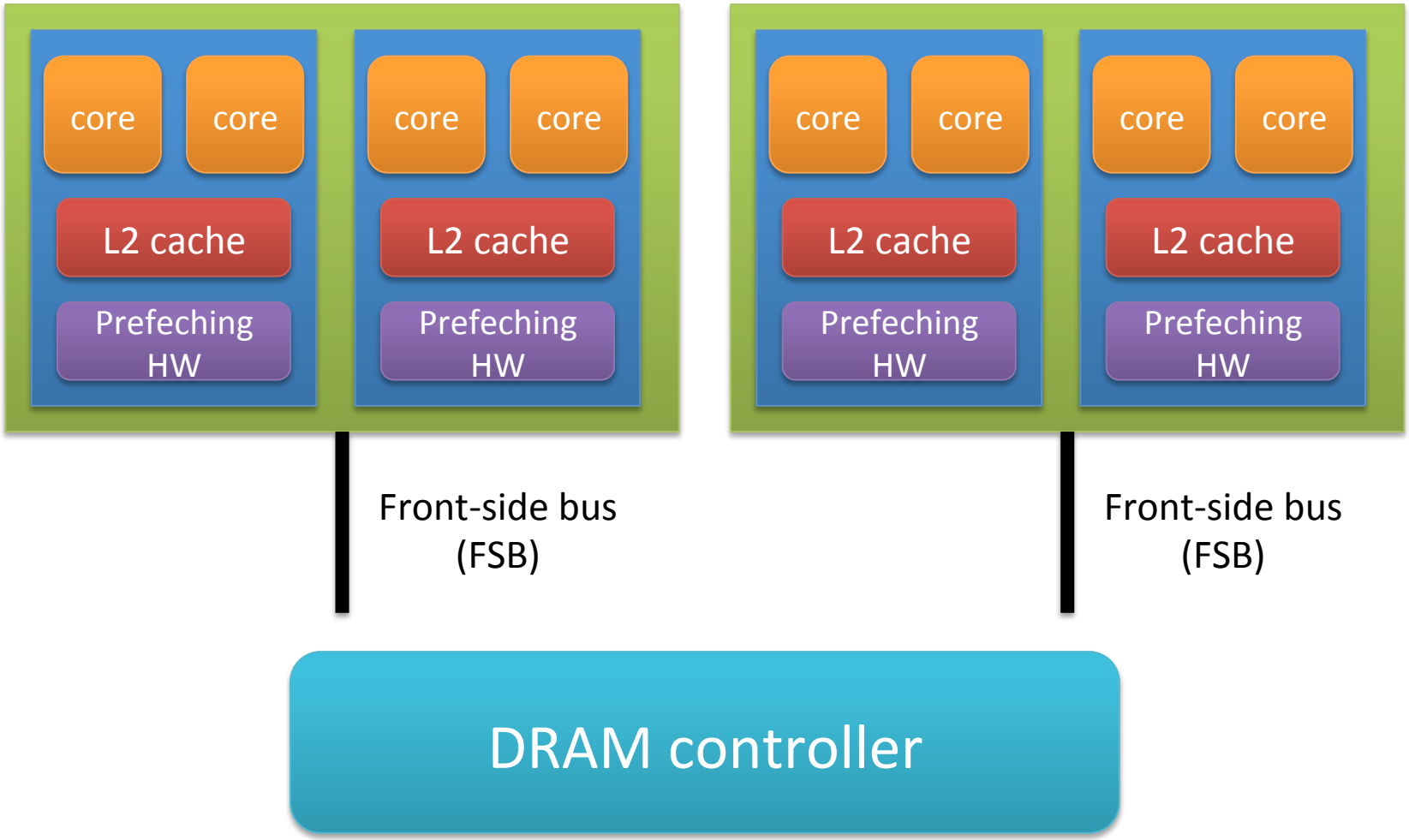
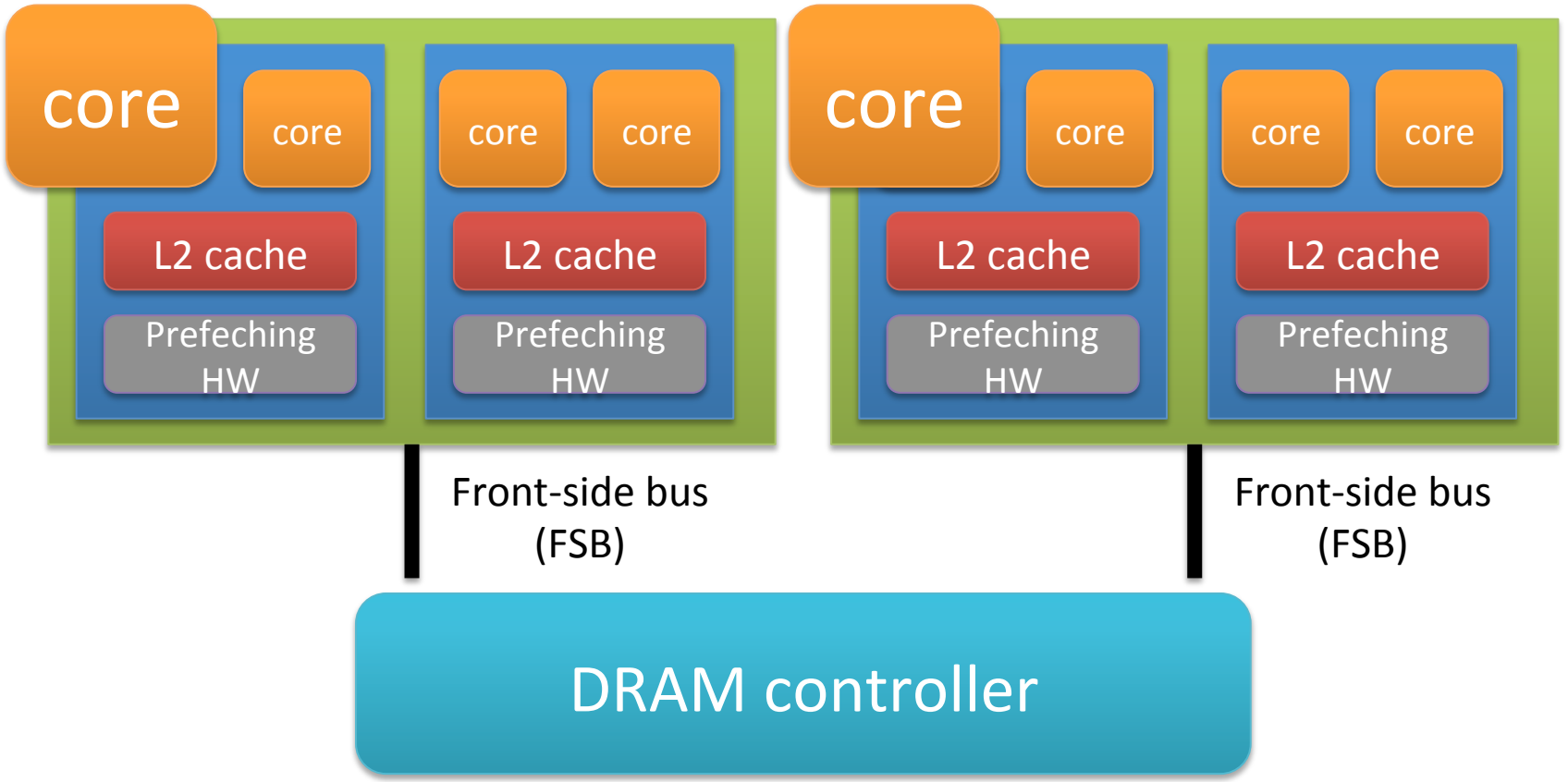



**Figure 3.** Degradation relative to optimal experienced by each classification scheme on systems with different numbers of cores.

# Performance Degradation Factors



# DRAM Contention




$$DRAM\ contention = \frac{DiffSocketPrefetchOFF - SoloPrefetchOFF}{SoloPrefetchOFF}$$

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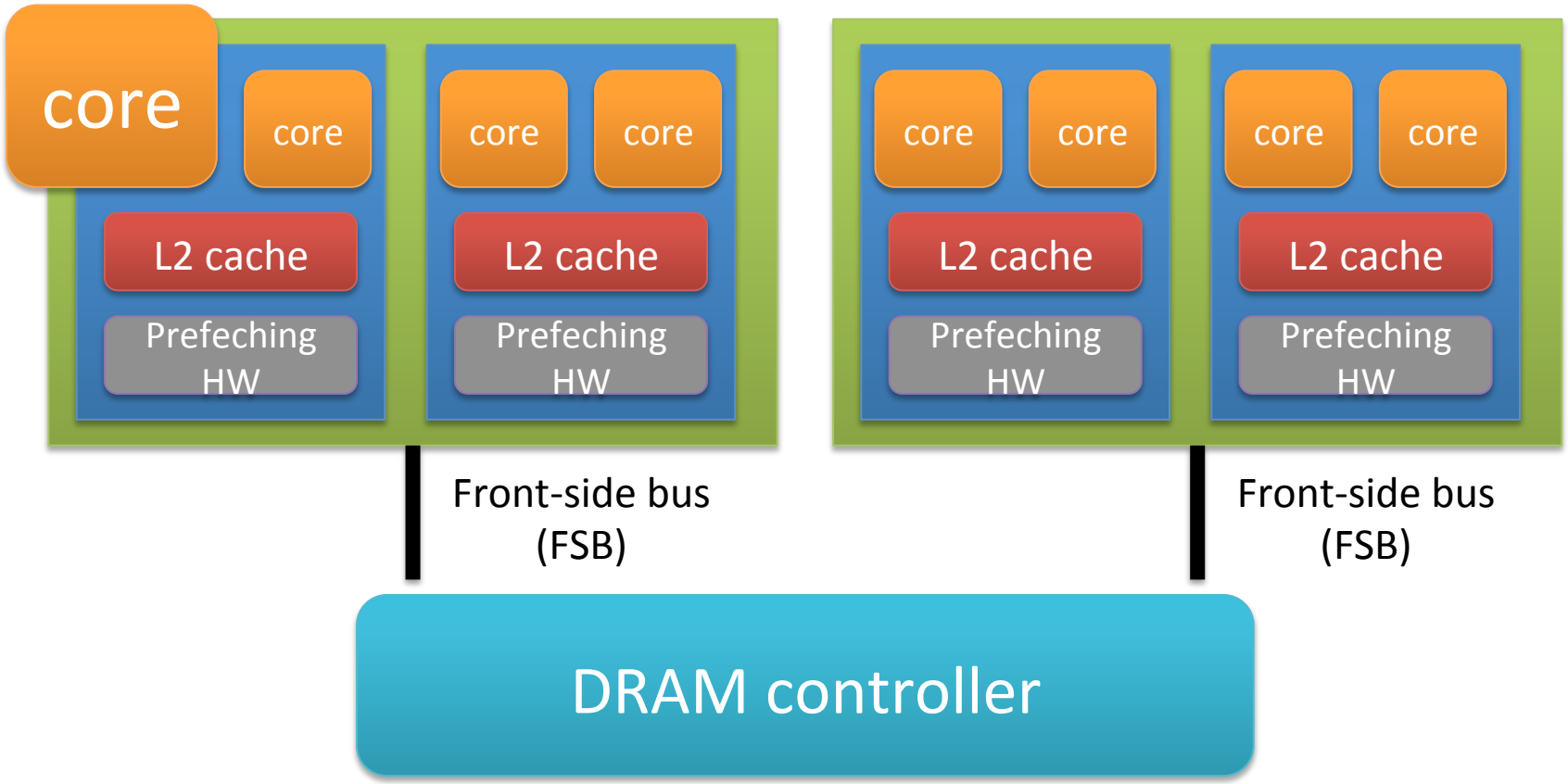
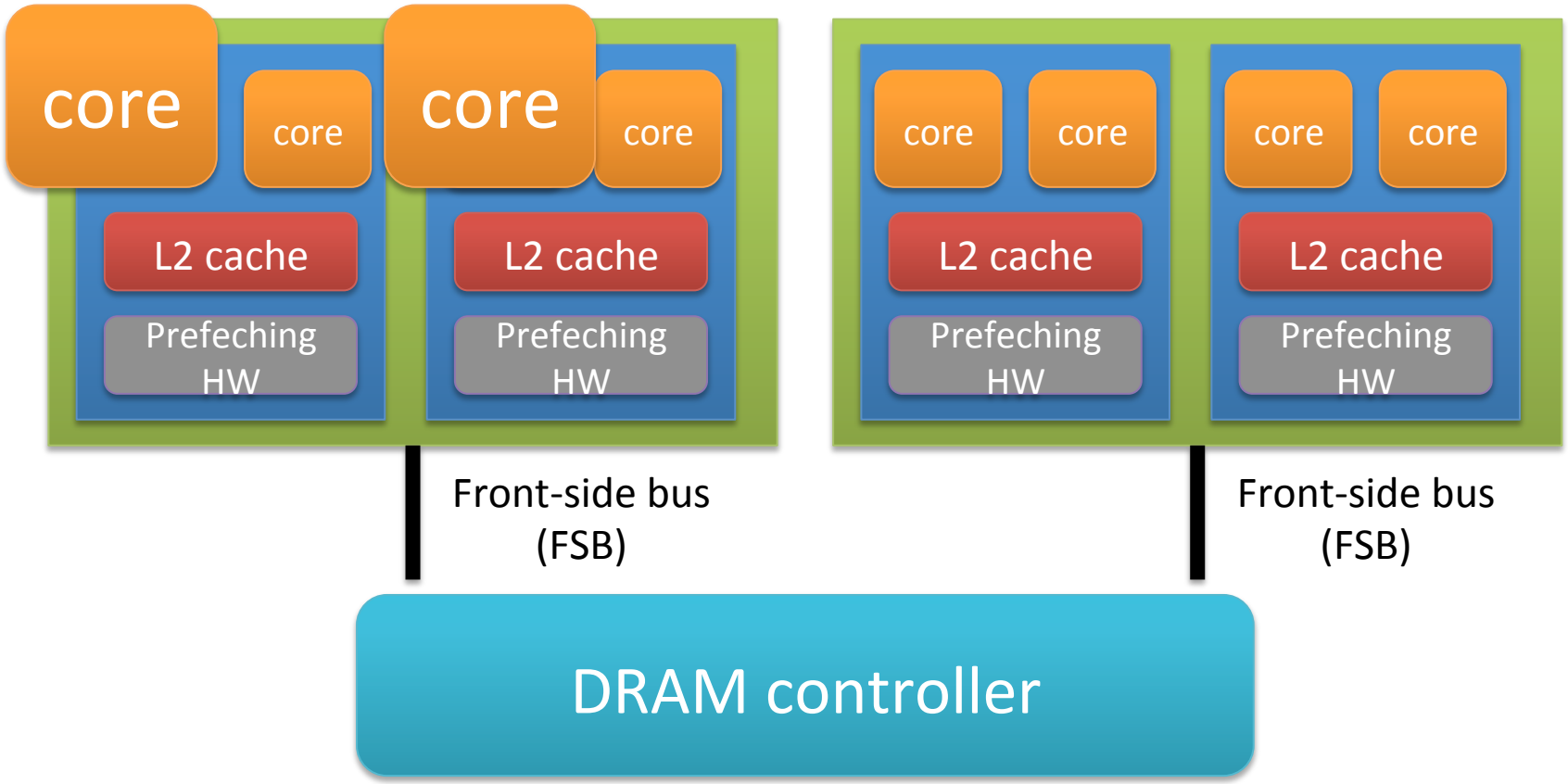


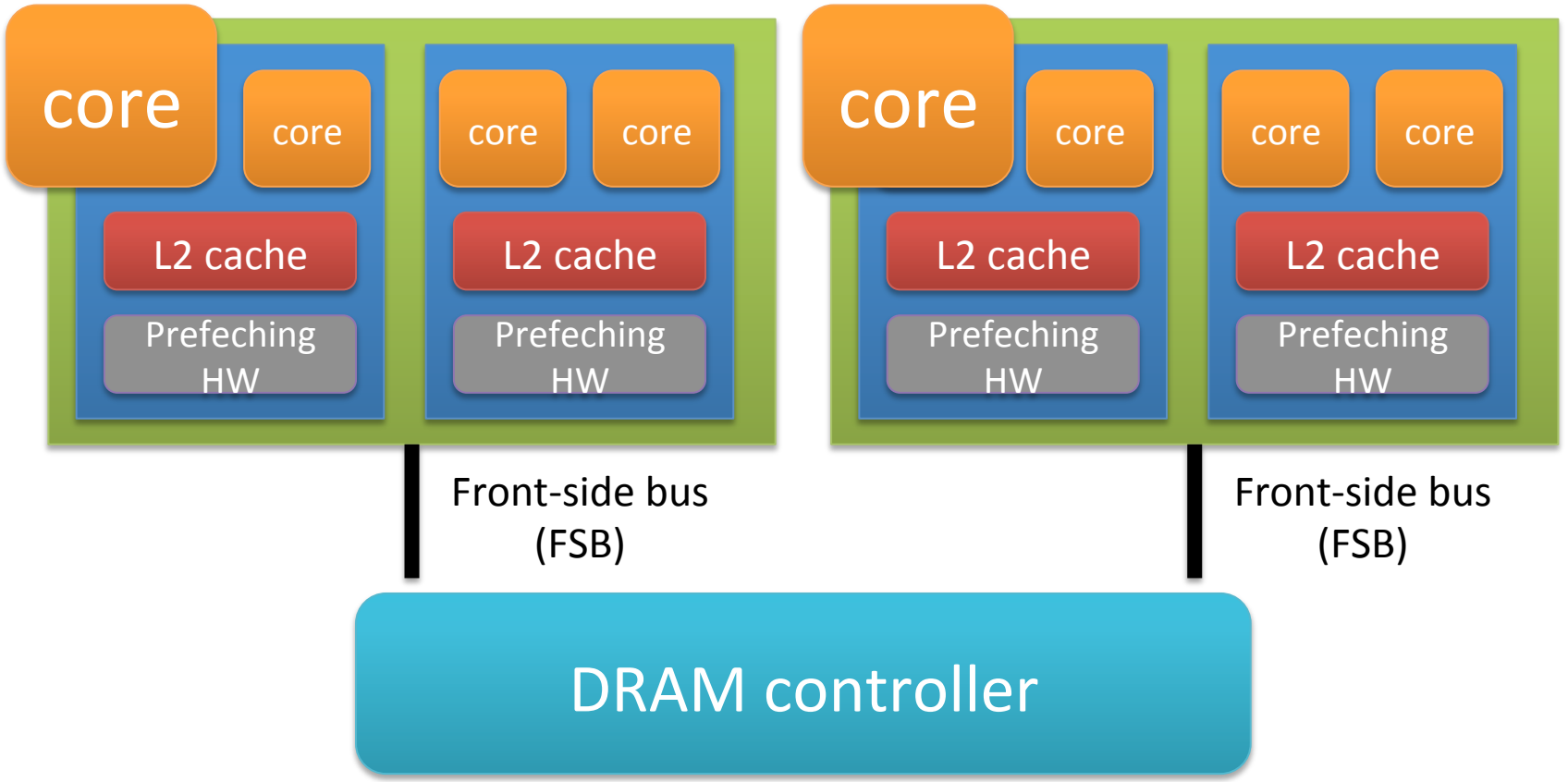

$$DRAM\ contention = \frac{DiffSocketPrefetchOFF - SoloPrefetchOFF}{SoloPrefetchOFF}$$

# FSB Contention




$$FSB\ contention = \frac{DiffCachePrefetchOFF - DiffSocketPrefetchOFF}{SoloPrefetchOFF}$$

# FSB Contention

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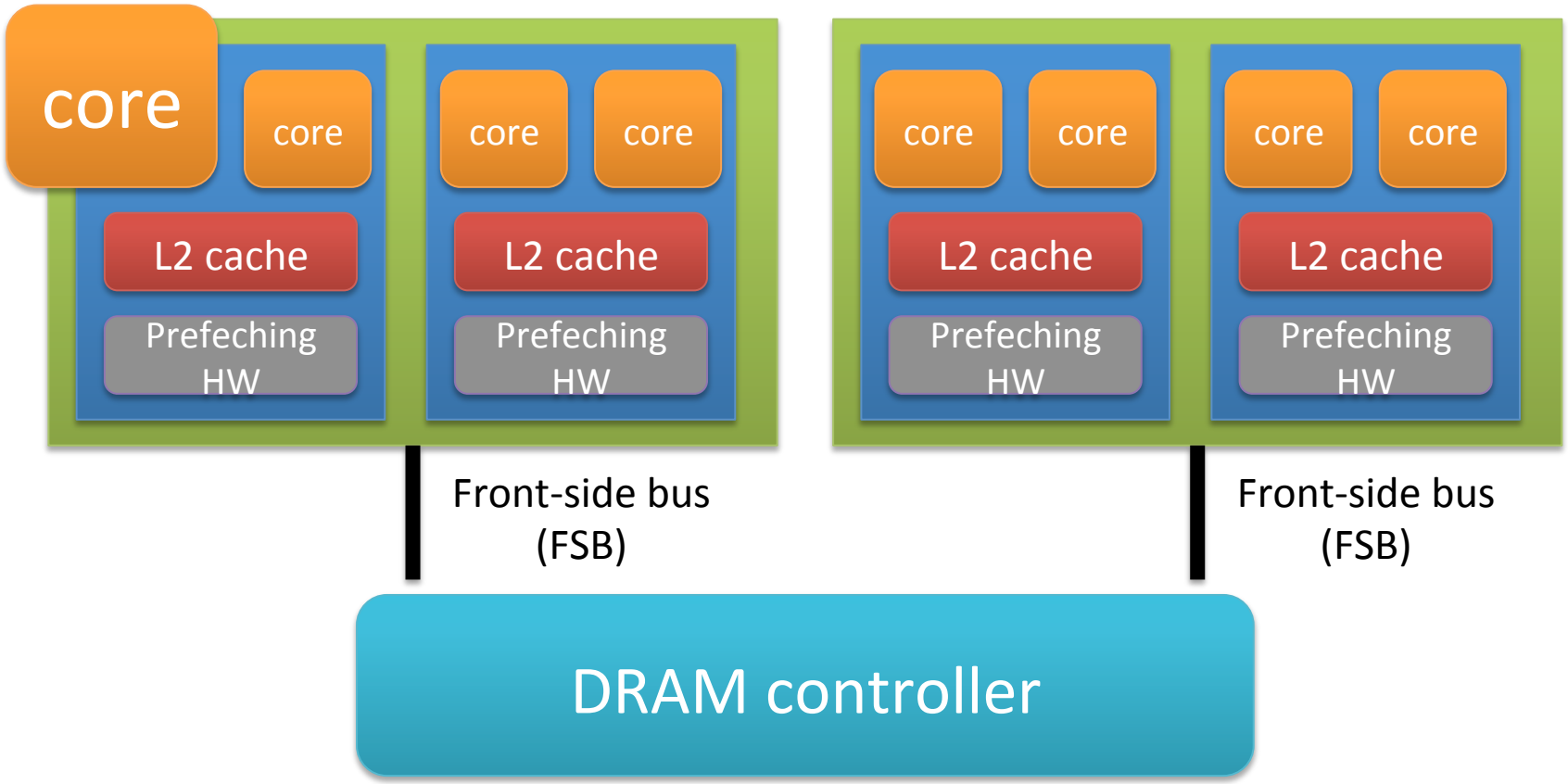
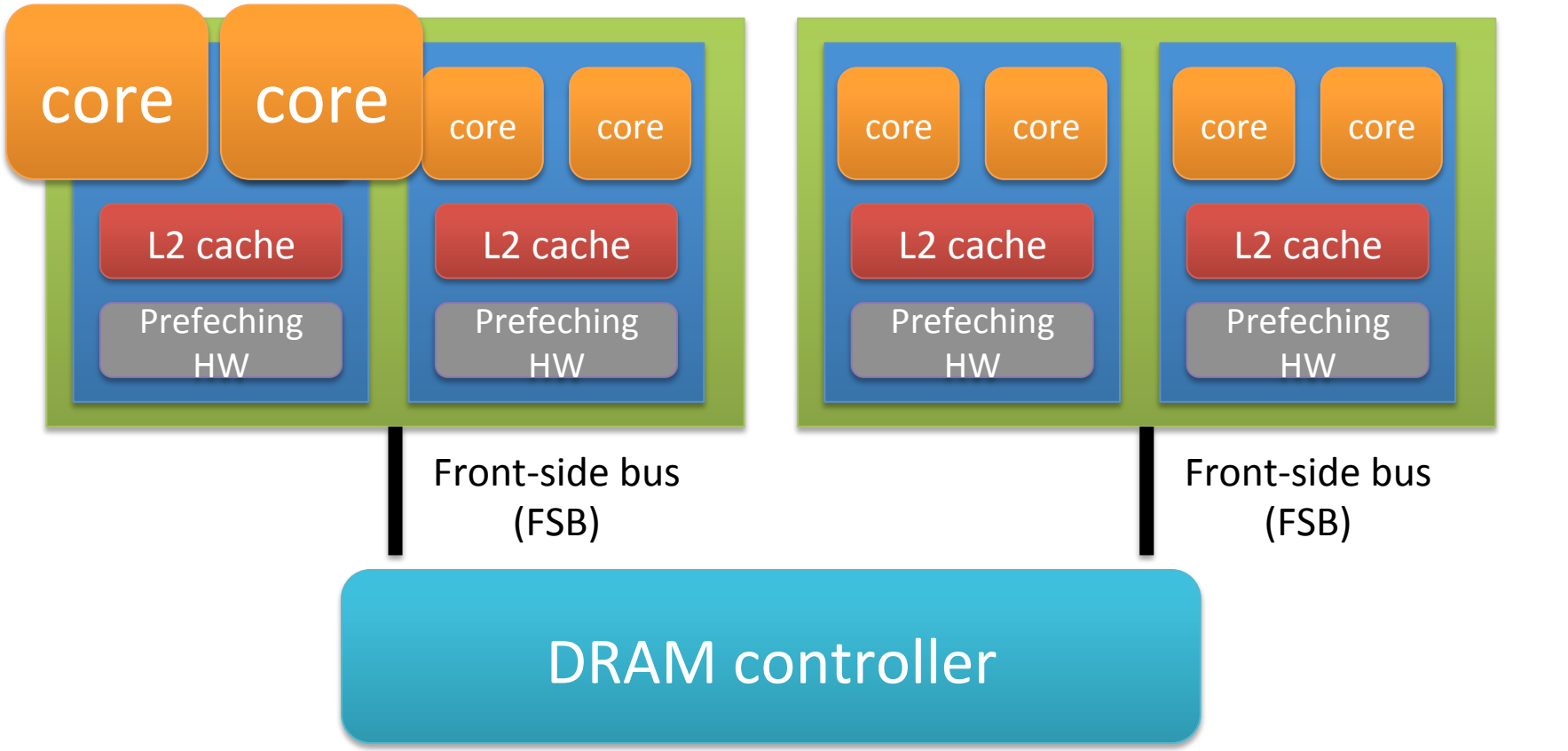


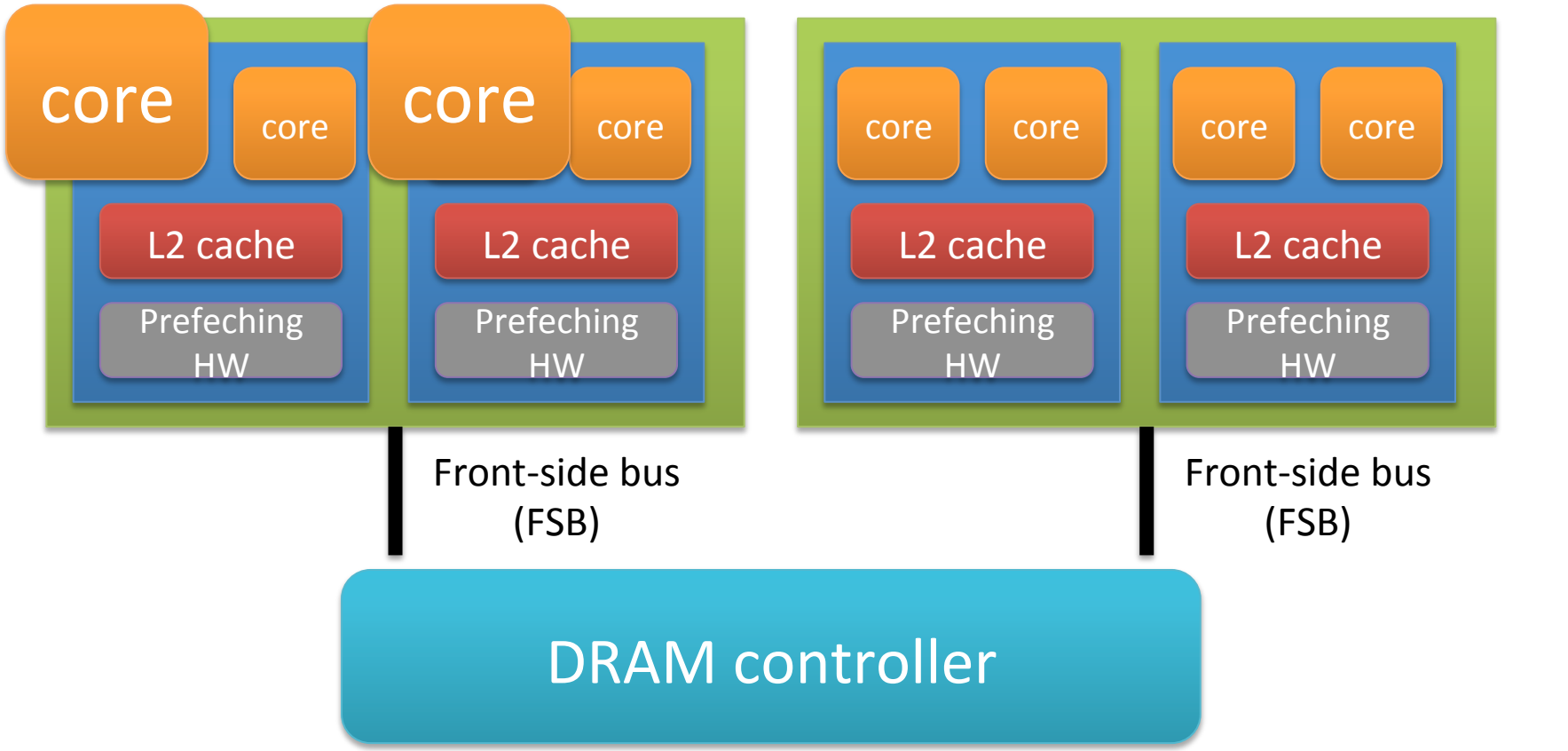

$$FSB\ contention = \frac{DiffCachePrefetchOFF - DiffSocketPrefetchOFF}{SoloPrefetchOFF}$$

# Cache Contention




$$Cache\ contention = \frac{SameCachePrefetchOFF - DiffCachePrefetchOFF}{SoloPrefetchOFF}$$

# Cache Contention

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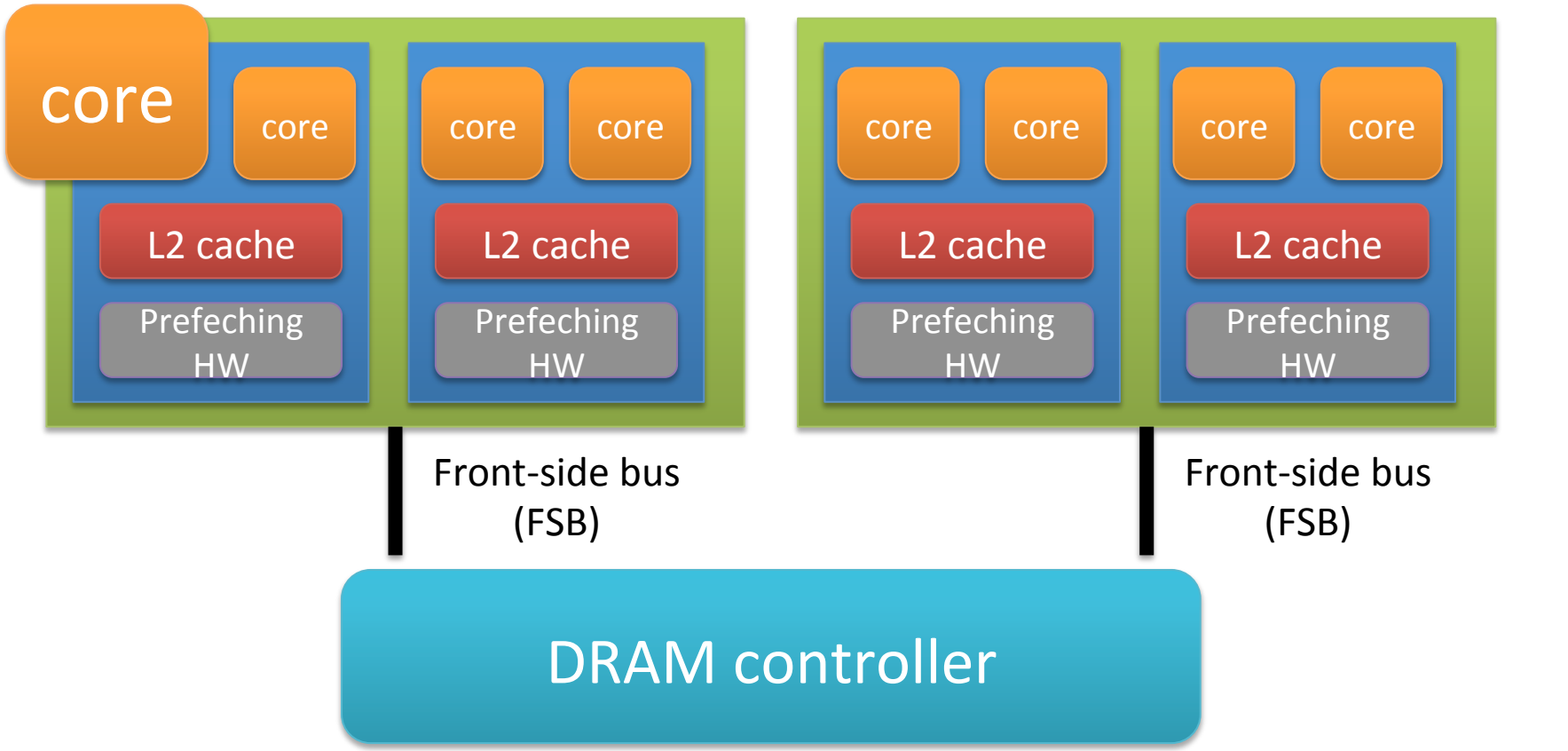
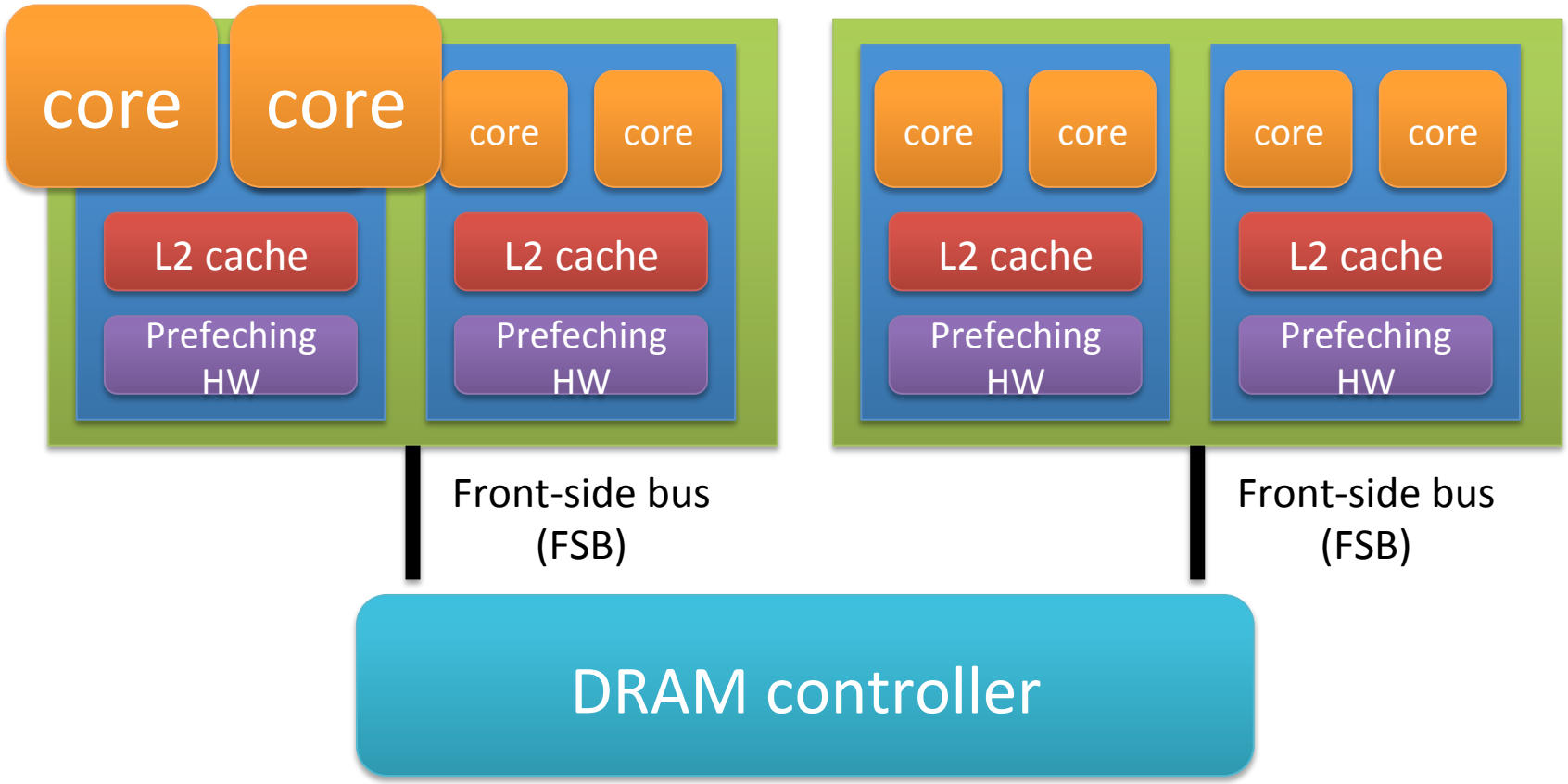


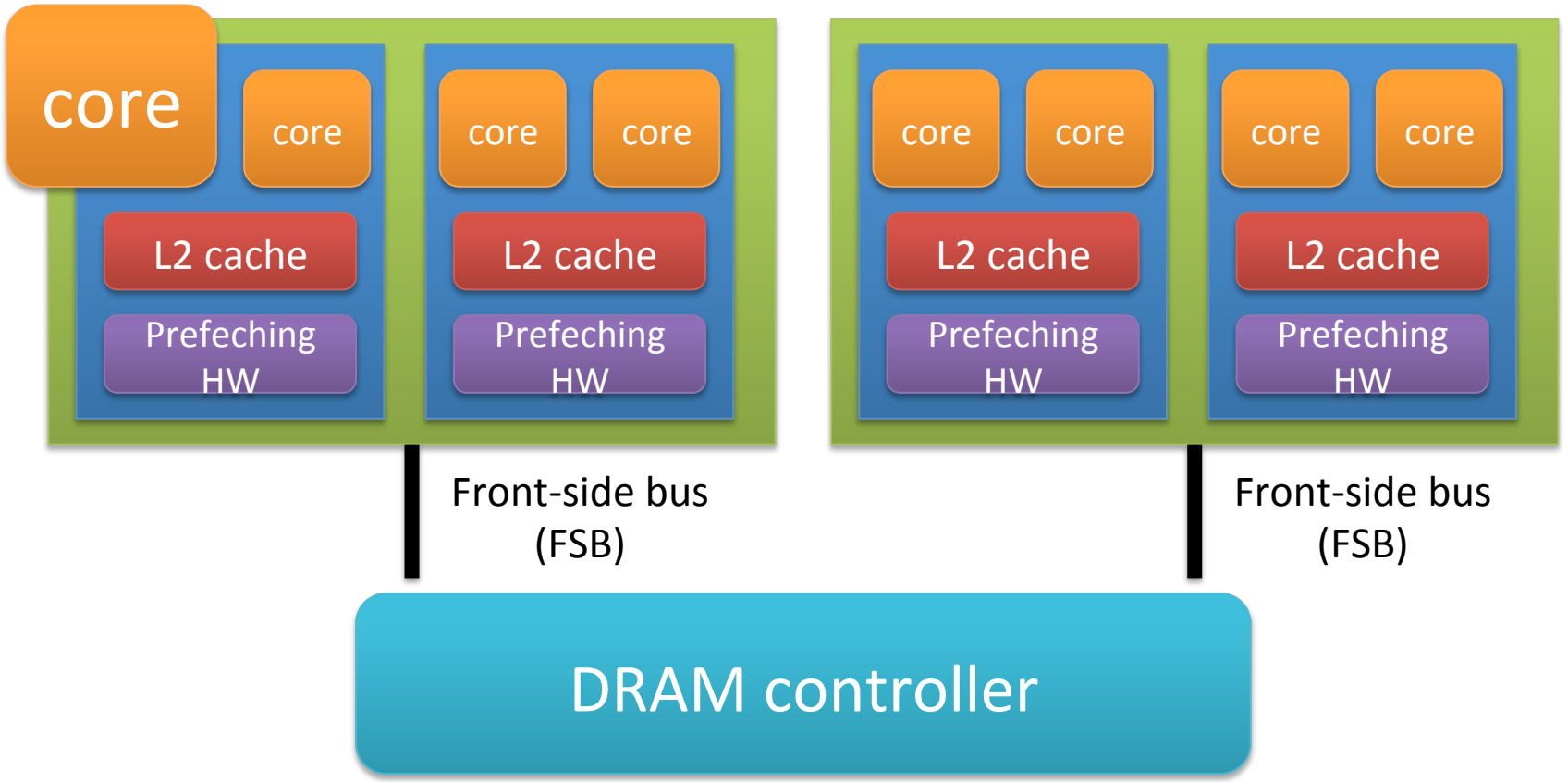

$$Cache\ contention = \frac{SameCachePrefetchOFF - DiffCachePrefetchOFF}{SoloPrefetchOFF}$$

# Total Degradation




$$Total\ Degradation = \frac{SameCachePrefetchON - SoloPrefetchON}{SoloPrefetchON}$$

# Total Degradation




$$Total\ Degradation = \frac{SameCachePrefetchON - SoloPrefetchON}{SoloPrefetchON}$$

# Prefeching Contention

Prefeching Contention =

Total Degradation (PF ON)

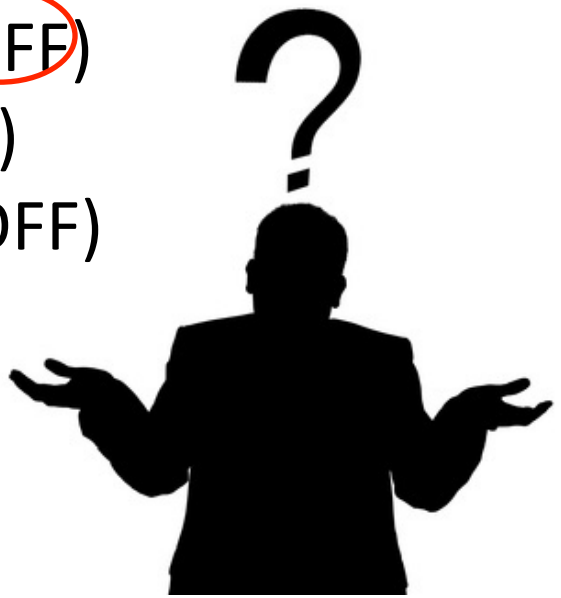
- Cache Contention (PF OFF)
- FSB Contention (PF OFF)
- DRAM Contention (PF OFF)

# Prefetching Contention

Prefetching Contention =

Total Degradation (PF ON)

- Cache Contention (PF OFF)
- FSB Contention (PF OFF)
- DRAM Contention (PF OFF)



# Contributions of Degradation Factors

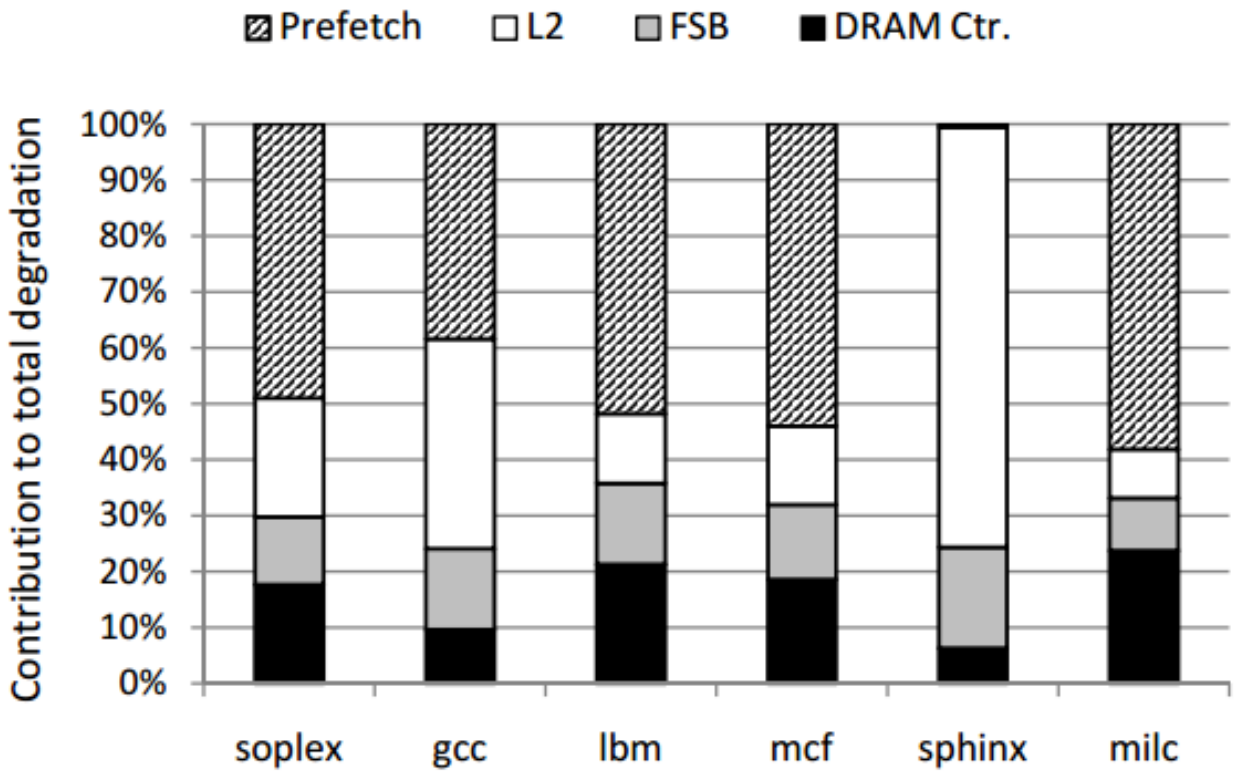



**Figure 4.** Percent contribution that each of the factors have on the total degradation.

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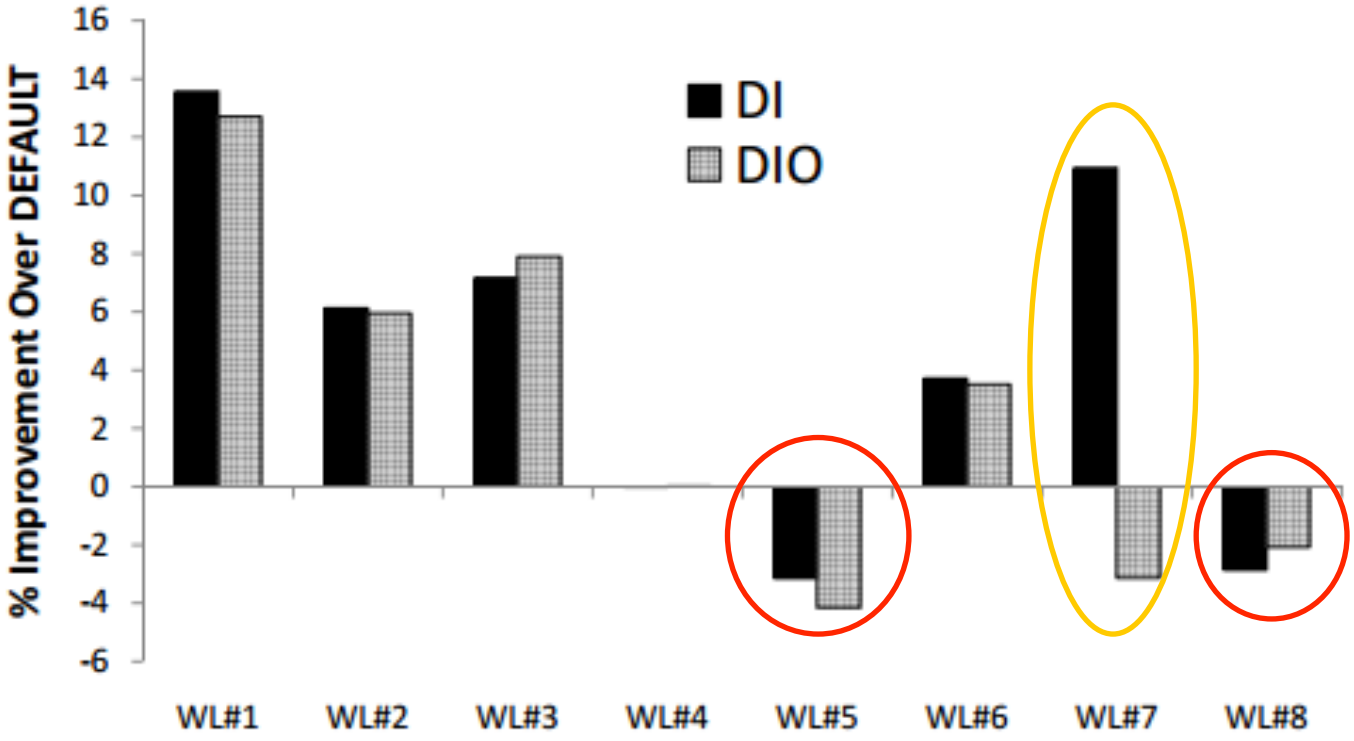
# Scheduling Algorithms

- Pick one classification scheme
  - Pain is the best (offline), but overhead is big
  - Picked miss rate
- Distributed Intensity (DI)
  - Sort based on solo miss rate
  - Goal: miss rates are distributed evenly
- Distributed intensity Online (DIO)
  - Get miss rate dynamically

# Average Performance

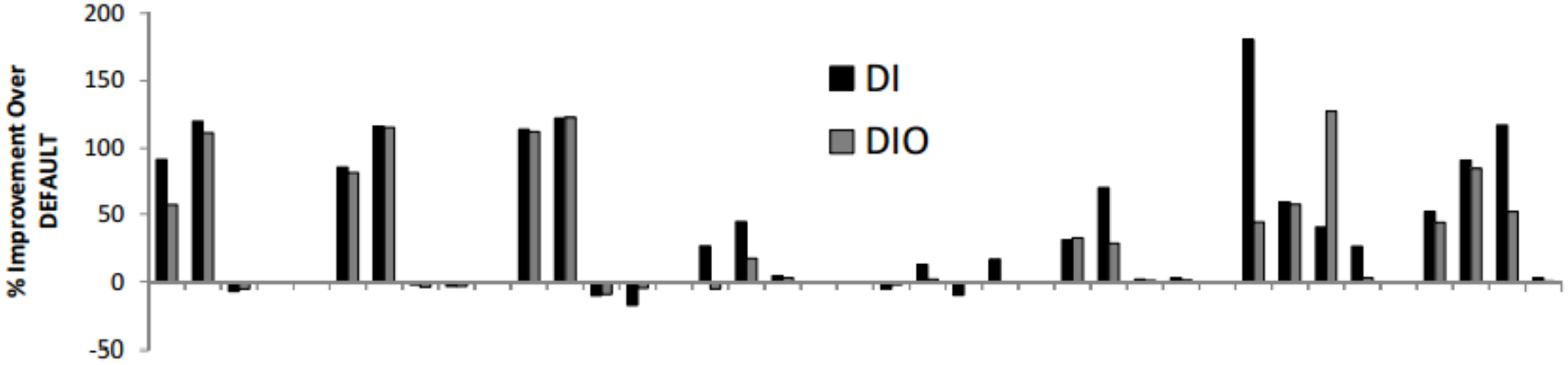
- Intel Xeon X5365; Eight workloads
- Compare to DEFAULT (Linux scheduler)



# Not much Better?

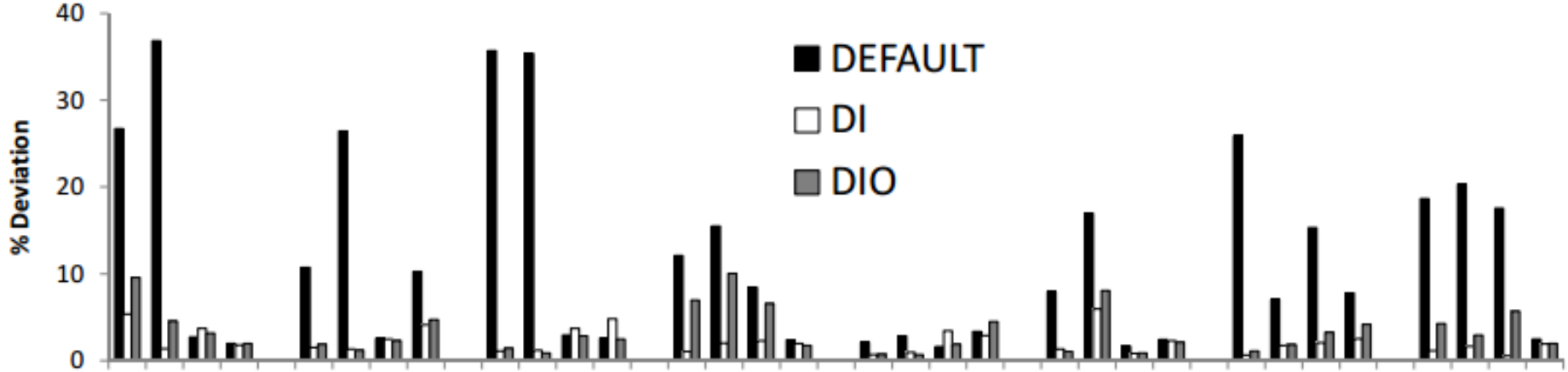
- Consider a case where
  - Four cores; two shared cache
  - Two intensive applications (high miss rate), two non-intensive applications (low miss rate)
- DI/DIO makes sure the two intensive ones don't run together
- But the worst case only happens with 1/3 probability…

# Worst-case Performance




(a) The relative performance improvement of the worst case DI and DIO over the worst case DEFAULT for Intel 8 threads.

# Performance deviation




(b) Deviation of the same application in the same workload with DI, DIO and Default (low bars are good) for Intel 8 threads.

# Conclusions

- Cache contention is NOT the dominant cause (?)
- Evaluated different classification schemes
  - Pain is the best; miss rate is the most practical
- Miss rate performs well in real scheduling
- Contention-aware scheduling is good for
  - Improving average performance (not so much)
  - QoS & performance isolation

# Other papers…

- Fine grained scheduling
  - Software scheduling overhead is too high, hardware?
- Contention for shared resource (critical section)
  - Optimizing for locks
- Scheduling at Clusters
  - A node has multiple VMs, a VM has multiple threads