Computer Architecture

Lecture 13a: Memory Controllers: Service Quality

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9 November 2023

Recall: Memory Controllers and Shared Resources

DRAM vs. Other Types of Memories

- Long latency memories have similar characteristics that need to be controlled.

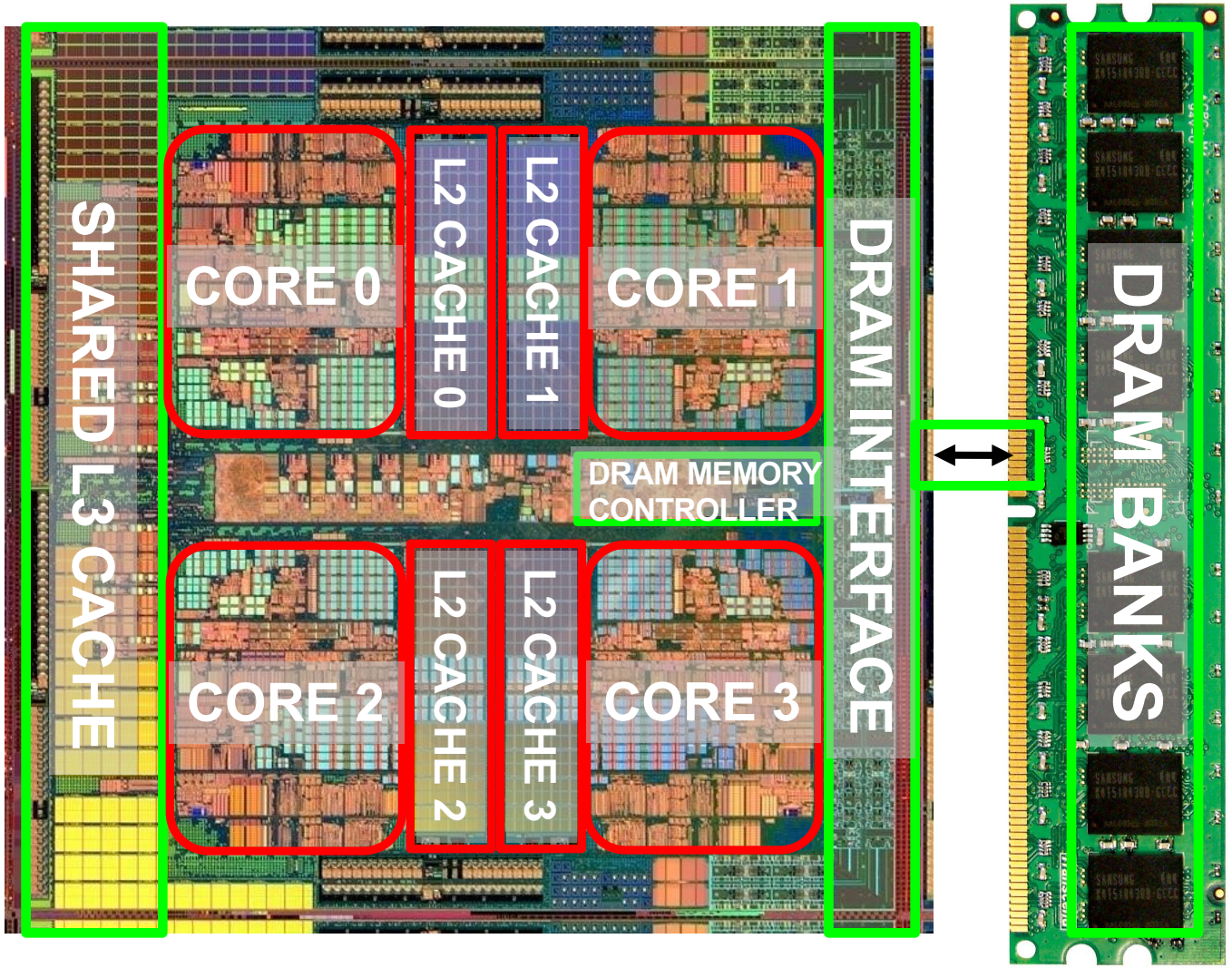
- This lecture will use DRAM as an example, but many scheduling and control issues are similar in the design of controllers for other types of memories
  - Flash memory
  - Other emerging memory technologies
    - Phase Change Memory
    - Spin-Transfer Torque Magnetic Memory
  - These other technologies can also place other demands on the controller

DRAM Types

- DRAM has different types with different interfaces optimized for different purposes
  - Commodity: DDR, DDR2, DDR3, DDR4, DDR5, …
  - Low power (for mobile): LPDDR1, …, LPDDR5, …
  - High bandwidth (for graphics): GDDR2, …, GDDR5, …
  - Low latency: eDRAM, RLDRAM, …
  - 3D stacked: WIO, HBM, HMC, HBM2.0, …
  - …
- Underlying microarchitecture is fundamentally the same
- A flexible memory controller can support various DRAM types
- This complicates the memory controller
  - Difficult to support all types (and upgrades)
  - Analog interface is different for different DRAM types

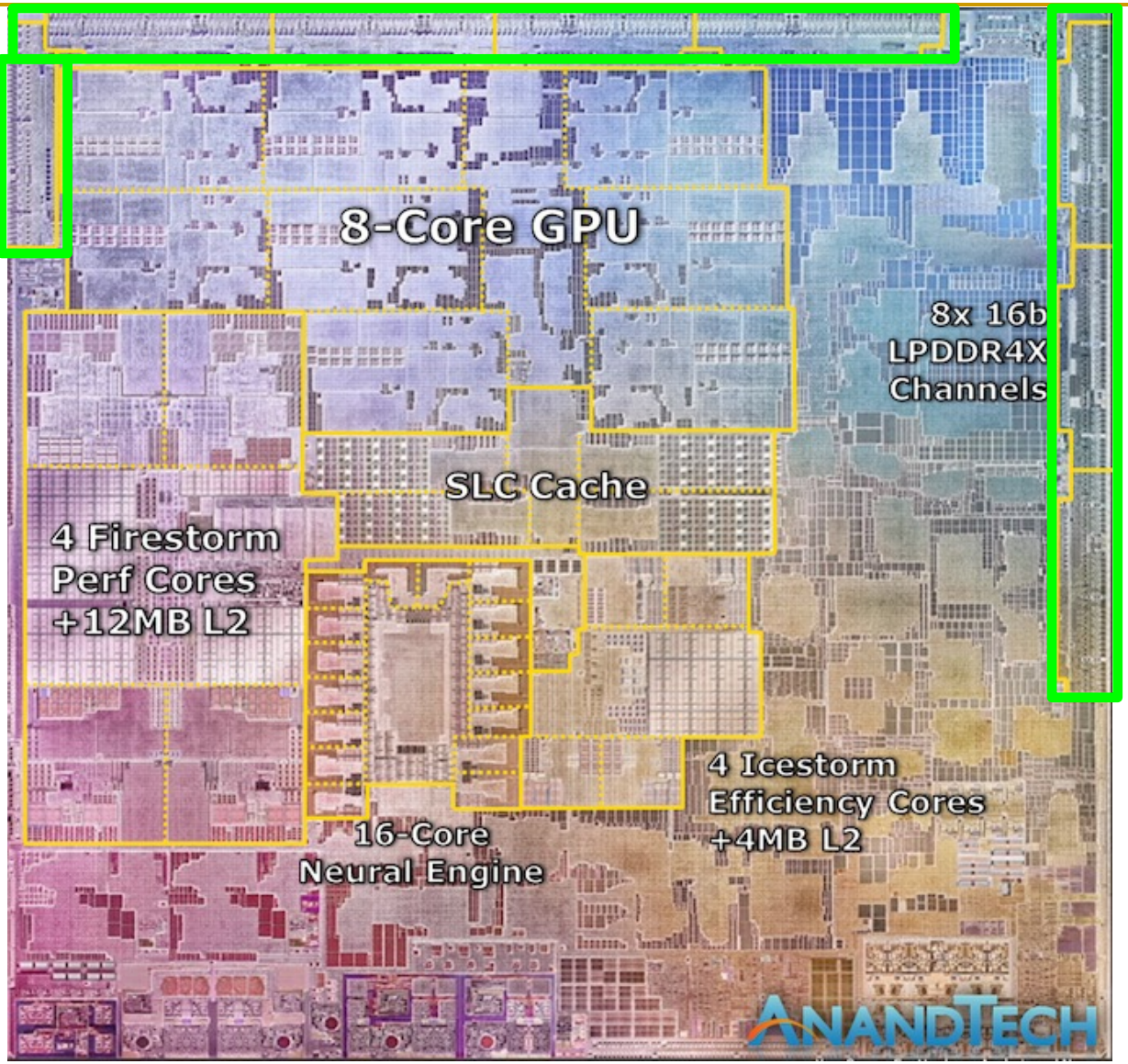
DRAM Control Logic Is Large

Multi-Core Chip



*Die photo credit: AMD Barcelona

DRAM Control Logic Is Large



Apple M1, 2021

Source: https://www.anandtech.com/show/16252/mac-mini-apple-m1-tested

DRAM Controller: Functions

- Ensure correct operation of DRAM (refresh and timing)
- Service DRAM requests while obeying timing constraints of DRAM chips
  - Constraints: resource conflicts (bank, bus, channel), minimum write-to-read delays
  - Translate requests to DRAM command sequences
- Buffer and schedule requests for high performance + QoS
  - Reordering, row-buffer, bank, rank, bus management
- Manage power consumption and thermals in DRAM
  - Turn on/off DRAM chips, manage power modes

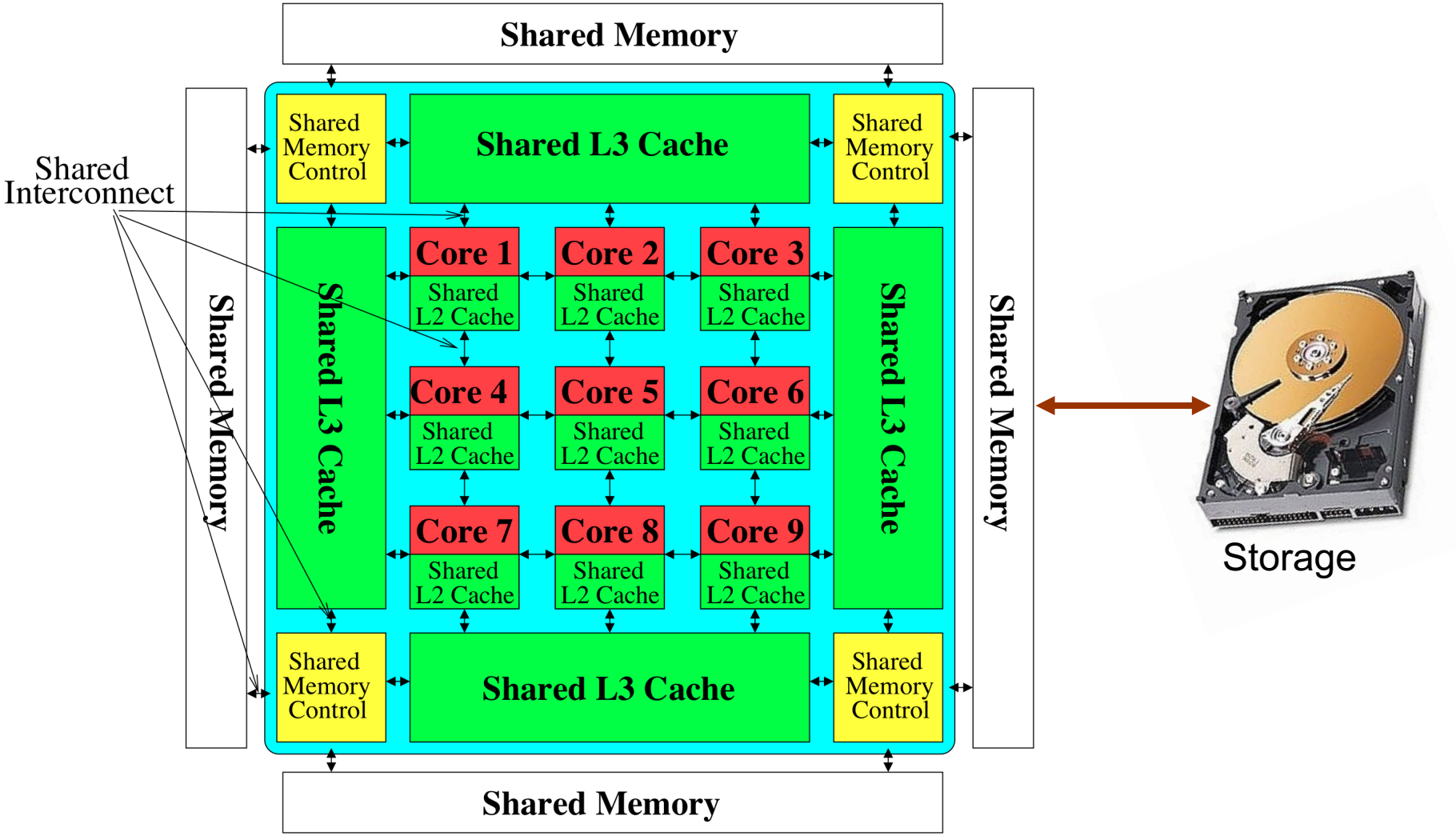
DRAM Scheduling Policies

- A scheduling policy is a request prioritization order

- Prioritization can be based on
  - Request age
  - Row buffer hit/miss status
  - Request type (prefetch, read, write)
  - Requestor type (load miss or store miss)
  - Request criticality
    - Oldest miss in the core?
    - How many instructions in core are dependent on it?
    - Will it stall the processor?
  - Interference caused to other cores
  - ...

Shared Resource Design for Multi-Core Systems

Memory System: A *Shared Resource* View



Most of the system is dedicated to storing and moving data

Resource Sharing Concept

- Idea: Instead of dedicating a hardware resource to a hardware context, allow multiple contexts to use it
  - Example resources: functional units, pipeline, caches, buses, memory, interconnects, storage
- Why?

+ Resource sharing improves utilization/efficiency → throughput
  - When a resource is left idle by one thread, another thread can use it; no need to replicate shared data
+ Reduces communication latency
  - For example, shared data kept in the same cache in SMT processors
+ Compatible with the shared memory model

Resource Sharing Disadvantages

- Resource sharing results in contention for resources
  - When the resource is not idle, another thread cannot use it
  - If space is occupied by one thread, another thread needs to re-occupy it

- Sometimes reduces each or some thread's performance
  - Thread performance can be worse than when it is run alone
- Eliminates performance isolation → inconsistent performance across runs
  - Thread performance depends on co-executing threads
- Uncontrolled (free-for-all) sharing degrades QoS
  - Causes unfairness, starvation

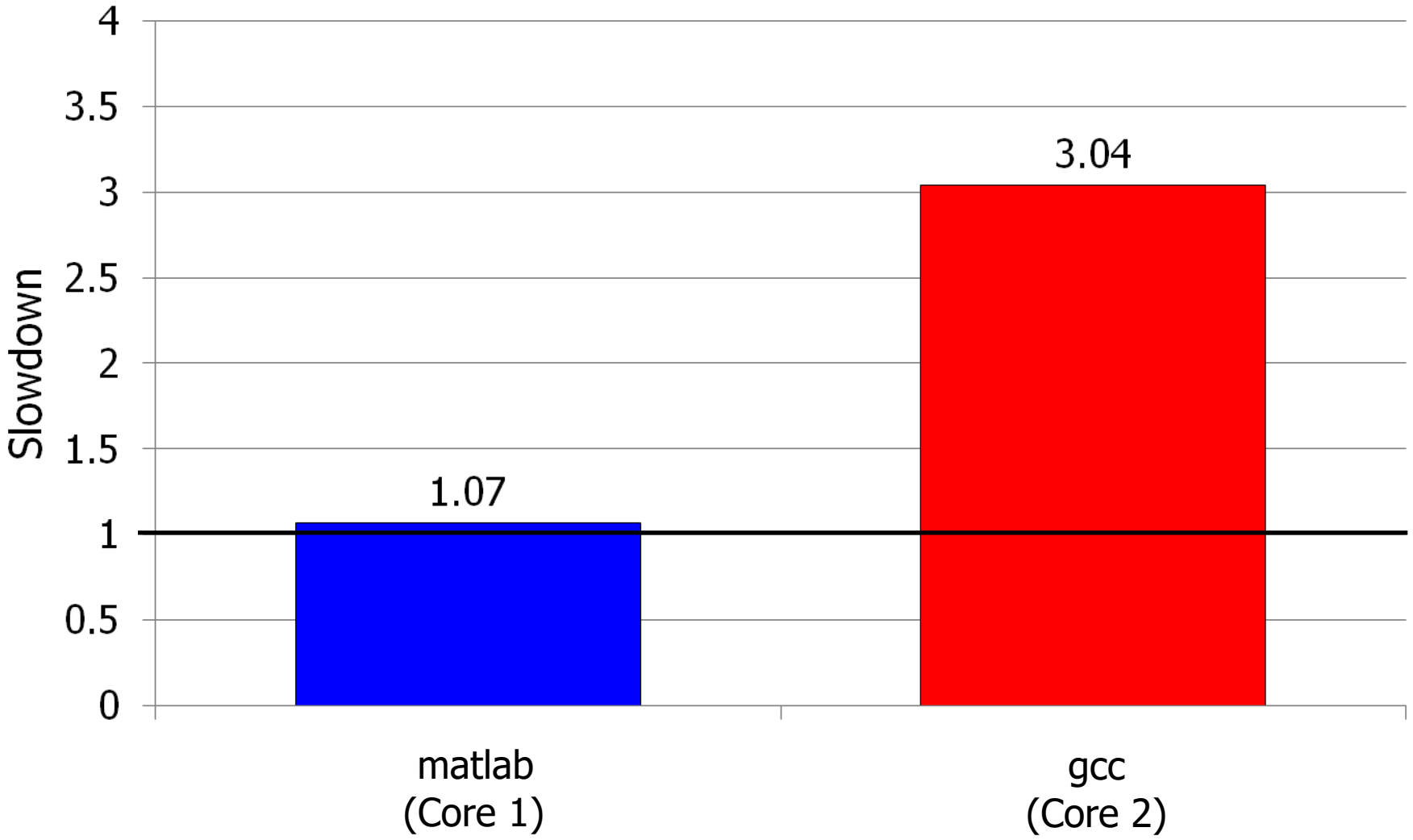
Need to efficiently and fairly utilize shared resources

Inter-Thread/Application Interference

- Problem: Threads share the memory system, but memory system does not distinguish between threads' requests

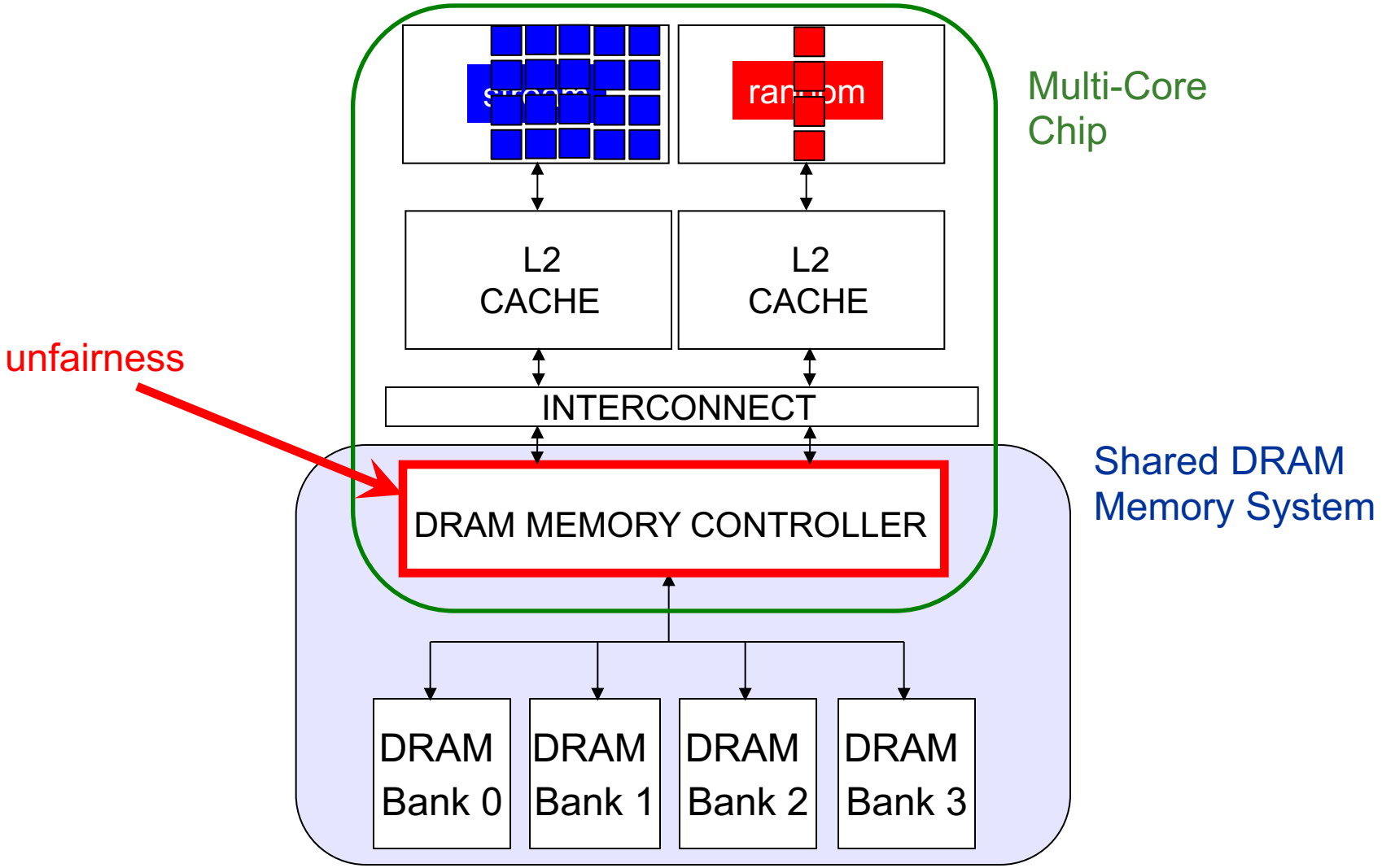
- Existing memory systems
  - Free-for-all, shared based on demand
  - Control algorithms thread-unaware and thread-unfair
  - Aggressive threads can deny service to others
  - Do not try to reduce or control inter-thread interference

Unfair Slowdowns due to Interference



Moscibroda and Mutlu, "Memory performance attacks: Denial of memory service in multi-core systems," USENIX Security 2007.

Uncontrolled Interference: An Example



A Memory Performance Hog

```
// initialize large arrays A, B

for (j=0; j<N; j++) {
    index = j*linesize;   streaming
    A[index] = B[index];
    …
}
```

```
// initialize large arrays A, B

for (j=0; j<N; j++) {
    index = rand();   random
    A[index] = B[index];
    …
}
```

STREAM

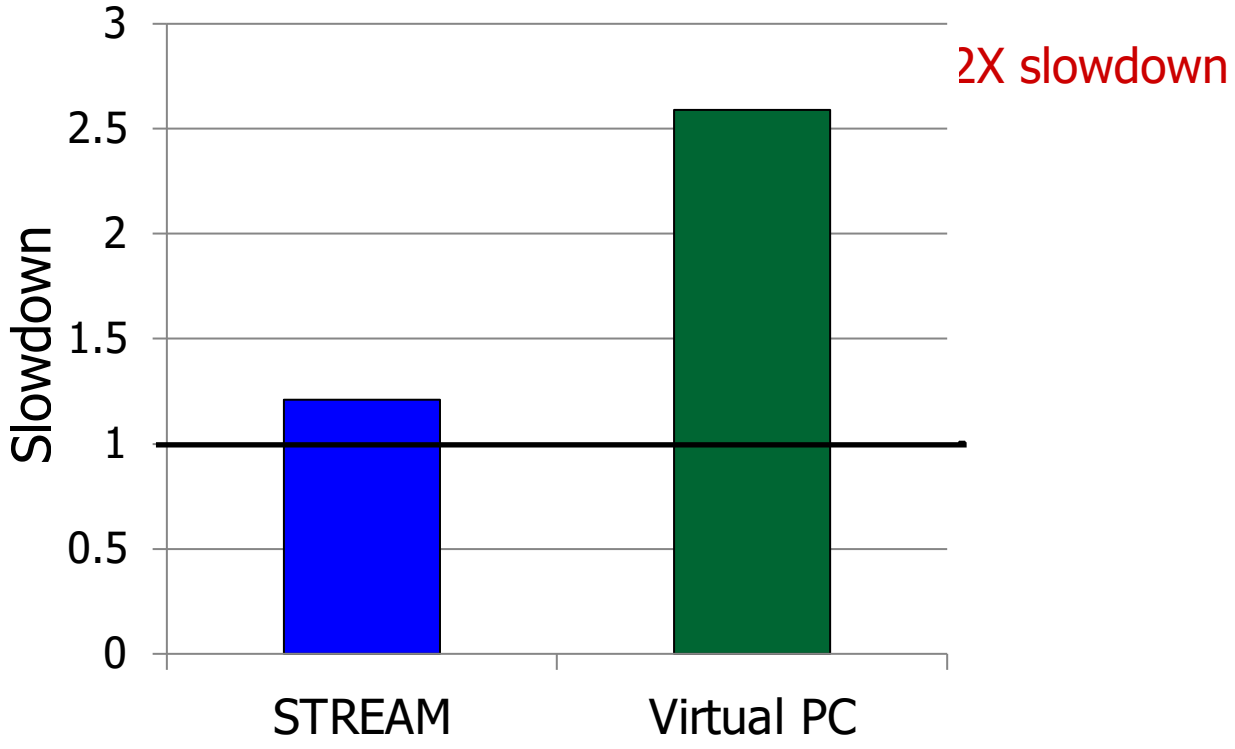
- Sequential memory access
- Very high row buffer locality (96% hit rate)
- Memory intensive

RANDOM

- Random memory access
- Very low row buffer locality (3% hit rate)
- Similarly memory intensive

Moscibroda and Mutlu, "Memory Performance Attacks," USENIX Security 2007.

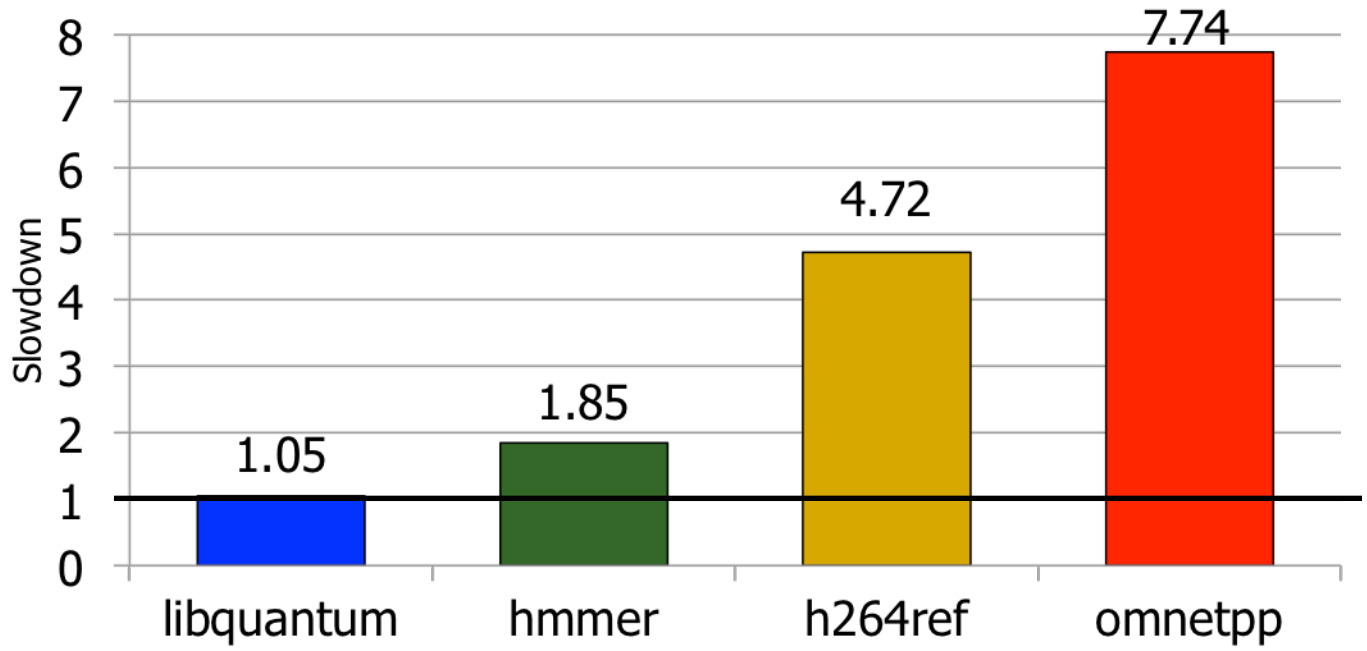
Effect of the Memory Performance Hog



Results on Intel Pentium D running Windows XP
(Similar results for Intel Core Duo and AMD Turion, and on Fedora Linux)

Moscibroda and Mutlu, "Memory Performance Attacks," USENIX Security 2007.

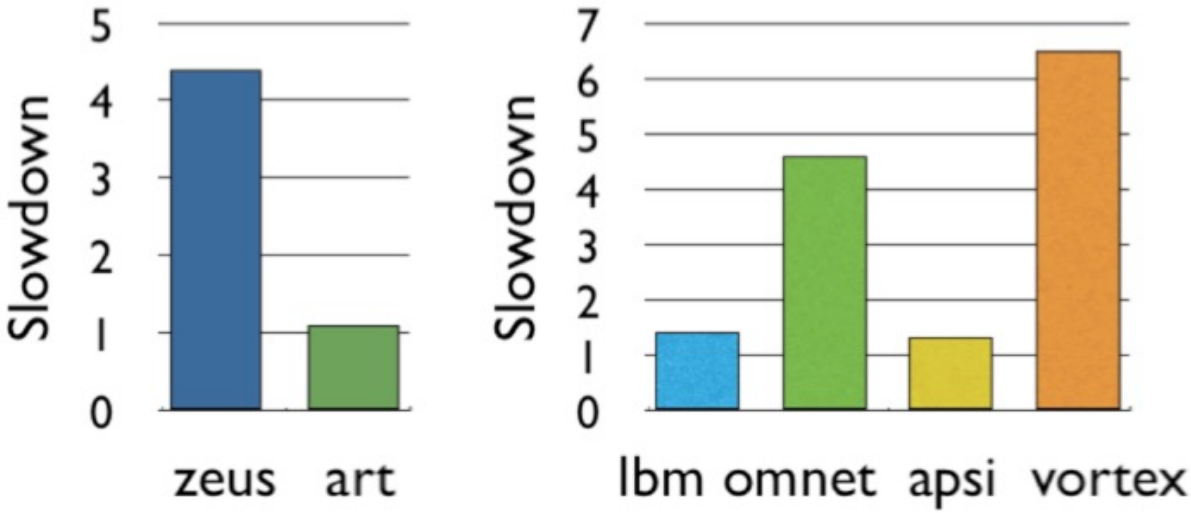
Greater Problem with More Cores



- Vulnerable to denial of service (DoS)
- Unable to enforce priorities or SLAs
- Low system performance

Uncontrollable, unpredictable system

Greater Problem with More Cores



- Vulnerable to denial of service (DoS)
- Unable to enforce priorities or SLAs
- Low system performance

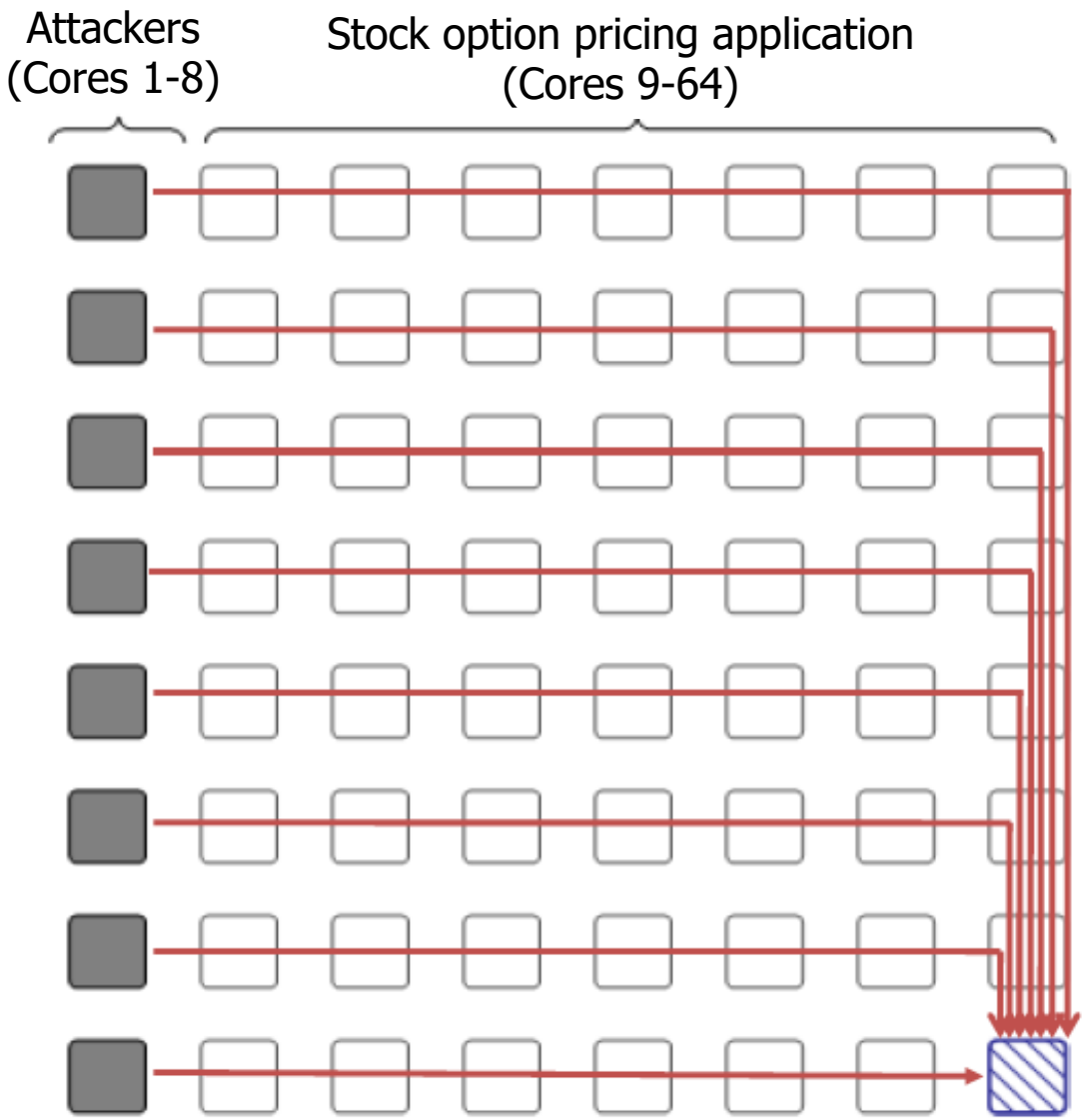
Uncontrollable, unpredictable system

Distributed DoS in Networked Multi-Core Systems

Cores connected via packet-switched routers on chip

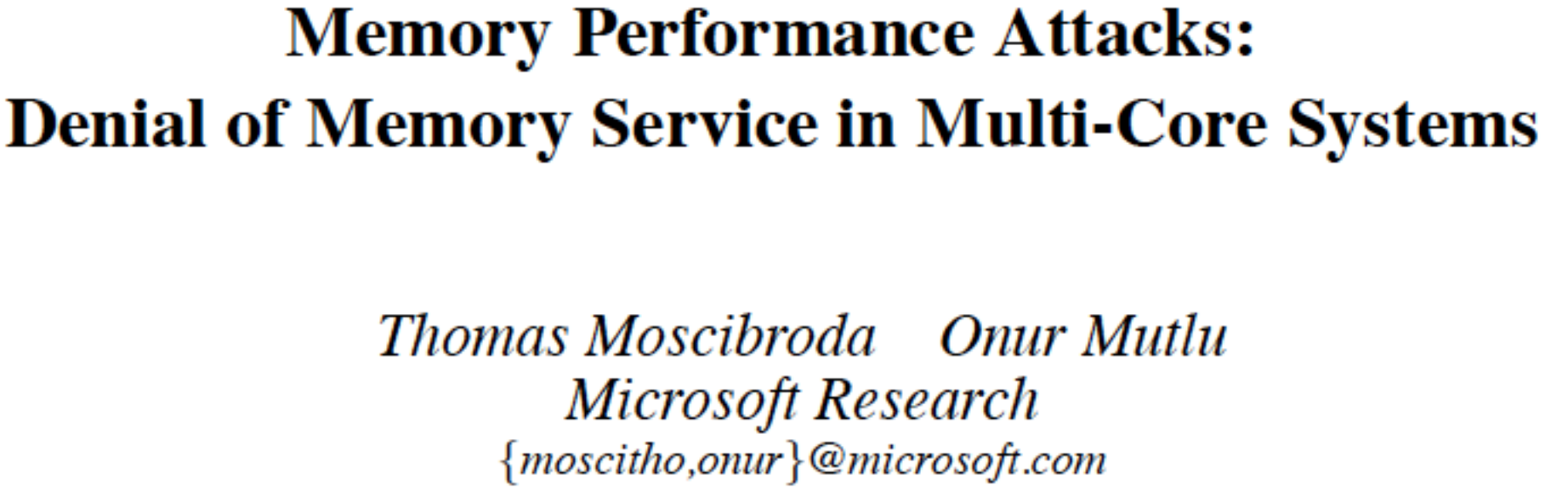
~5000X latency increase

Grot, Hestness, Keckler, Mutlu, "Preemptive virtual clock: A Flexible, Efficient, and Cost-effective QOS Scheme for Networks-on-Chip," MICRO 2009.



More on Memory Performance Attacks

- Thomas Moscibroda and Onur Mutlu,
  "Memory Performance Attacks: Denial of Memory Service in Multi-Core Systems"
  *Proceedings of the 16th USENIX Security Symposium (**USENIX SECURITY**)*, pages 257-274, Boston, MA, August 2007. Slides (ppt)



http://www.youtube.com/watch?v=VJzZbwgBfy8

More on Interconnect Based Starvation

- Boris Grot, Stephen W. Keckler, and Onur Mutlu, **"Preemptive Virtual Clock: A Flexible, Efficient, and Cost-effective QOS Scheme for Networks-on-Chip"** *Proceedings of the 42nd International Symposium on Microarchitecture (**MICRO**)*, pages 268-279, New York, NY, December 2009. Slides (pdf)

Preemptive Virtual Clock: A Flexible, Efficient, and Cost-effective QOS Scheme for Networks-on-Chip

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Carnegie Mellon University
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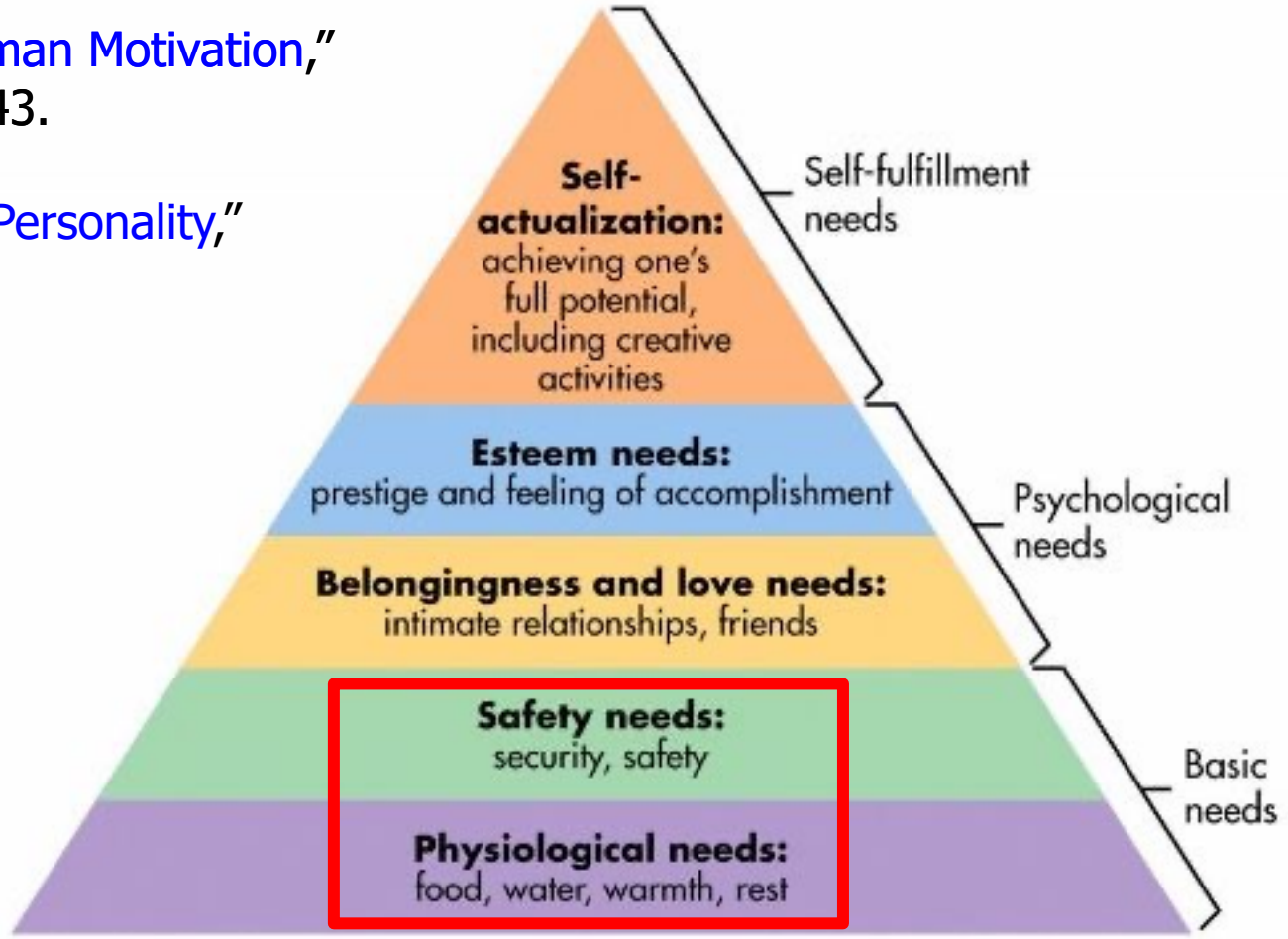
Maslow's (Human) Hierarchy of Needs

Maslow, "A Theory of Human Motivation," Psychological Review, 1943.

Maslow, "Motivation and Personality," Book, 1954-1970.



- Lack of QoS can be a safety and security problem

Source: https://www.simplypsychology.org/maslow.html

Source: By User:Factoryjoe - Mazlow's Hierarchy of Needs.svg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=7964065

How Do We Solve The Problem?

- Inter-thread interference is uncontrolled in all memory resources
  - Memory controller
  - Interconnect
  - Caches

- We need to control it
  - i.e., design an interference-aware (QoS-aware) memory system

Fundamental Interference Control Techniques

- Goal: to reduce/control inter-thread memory interference

1. Prioritization or request scheduling

2. Data mapping to banks/channels/ranks

3. Core/source throttling

4. Application/thread scheduling

QoS-Aware Memory Scheduling: Revolution & Evolution

QoS-Aware Memory Scheduling: Evolution

- Stall-time fair memory scheduling [Mutlu+ MICRO'07]
  - Idea: Estimate and balance thread slowdowns
  - Takeaway: Proportional thread progress improves performance, especially when threads are "heavy" (memory intensive)

- Parallelism-aware batch scheduling [Mutlu+ ISCA'08, Top Picks'09]
  - Idea: Rank threads and service in rank order (to preserve bank parallelism); batch requests to prevent starvation
  - Takeaway: Preserving within-thread bank-parallelism improves performance; request batching improves fairness

- ATLAS memory scheduler [Kim+ HPCA'10]
  - Idea: Prioritize threads that have attained the least service from the memory scheduler
  - Takeaway: Prioritizing "light" threads improves performance

QoS-Aware Memory Scheduling: Evolution

- Thread cluster memory scheduling [Kim+ MICRO'10, Top Picks'11]
  - Idea: Cluster threads into two groups (latency vs. bandwidth sensitive); prioritize the latency-sensitive ones; employ a fairness policy in the bandwidth sensitive group
  - Takeaway: Heterogeneous scheduling policy that is different based on thread behavior maximizes both performance and fairness

- Integrated Memory Channel Partitioning and Scheduling [Muralidhara+ MICRO'11]
  - Idea: Only prioritize very latency-sensitive threads in the scheduler; mitigate all other applications' interference via channel partitioning
  - Takeaway: Intelligently combining application-aware channel partitioning and memory scheduling provides better performance than either

QoS-Aware Memory Scheduling: Evolution

- Parallel application memory scheduling [Ebrahimi+ MICRO'11]
  - Idea: Identify and prioritize limiter threads of a multithreaded application in the memory scheduler; provide fast and fair progress to non-limiter threads
  - Takeaway: Carefully prioritizing between limiter and non-limiter threads of a parallel application improves performance

- Staged memory scheduling [Ausavarungnirun+ ISCA'12]
  - Idea: Divide the functional tasks of an application-aware memory scheduler into multiple distinct stages, where each stage is significantly simpler than a monolithic scheduler
  - Takeaway: Staging enables the design of a scalable and relatively simpler application-aware memory scheduler that works on very large request buffers

QoS-Aware Memory Scheduling: Evolution

- MISE: Memory Slowdown Model [Subramanian+ HPCA'13]
  - Idea: Estimate the performance of a thread by estimating its change in memory request service rate when run alone vs. shared → use this simple model to estimate slowdown to design a scheduling policy that provides predictable performance or fairness
  - Takeaway: Request service rate of a thread is a good proxy for its performance; alone request service rate can be estimated by giving high priority to the thread in memory scheduling for a while

- ASM: Application Slowdown Model [Subramanian+ MICRO'15]
  - Idea: Extend MISE to take into account cache+memory interference
  - Takeaway: Cache access rate of an application can be estimated accurately and is a good proxy for application performance

QoS-Aware Memory Scheduling: Evolution

- BLISS: Blacklisting Memory Scheduler [Subramanian+ ICCD'14, TPDS'16]
  - Idea: Deprioritize (i.e., blacklist) a thread that has consecutively serviced a large number of requests
  - Takeaway: Blacklisting greatly reduces interference enables the scheduler to be simple without requiring full thread ranking

- DASH: Deadline-Aware Memory Scheduler [Usui+ TACO'16]
  - Idea: Balance prioritization between CPUs, GPUs and Hardware Accelerators (HWA) by keeping HWA progress in check vs. deadlines such that HWAs do not hog performance and appropriately distinguishing between latency-sensitive vs. bandwidth-sensitive CPU workloads
  - Takeaway: Proper control of HWA progress and application-aware CPU prioritization leads to better system performance while meeting HWA deadlines

QoS-Aware Memory Scheduling: Evolution

- Prefetch-aware shared resource management [Ebrahimi+ ISCA'11] [Ebrahimi+ MICRO'09] [Ebrahimi+ HPCA'09] [Lee+ MICRO'08'09]
  - Idea: Prioritize prefetches depending on how they affect system performance; even accurate prefetches can degrade performance of the system
  - Takeaway: Carefully controlling and prioritizing prefetch requests improves performance and fairness

- DRAM-Aware last-level cache policies and write scheduling [Lee+ HPS Tech Report'10] [Seshadri+ ISCA'14]
  - Idea: Design cache eviction and replacement policies such that they proactively exploit the state of the memory controller and DRAM (e.g., proactively evict data from the cache that hit in open rows)
  - Takeaway: Coordination of last-level cache and DRAM policies improves performance and fairness; writes should not be ignored

QoS-Aware Memory Scheduling: Evolution

- FIRM: Memory Scheduling for NVM [Zhao+ MICRO'14]
  - Idea: Carefully handle write-read prioritization with coarse-grained batching and application-aware scheduling
  - Takeaway: Carefully controlling and prioritizing write requests improves performance and fairness; write requests are especially critical in NVMs

- Criticality-Aware Memory Scheduling for GPUs [Jog+ SIGMETRICS'16]
  - Idea: Prioritize latency-critical cores' requests in a GPU system
  - Takeaway: Need to carefully balance locality and criticality to make sure performance improves by taking advantage of both

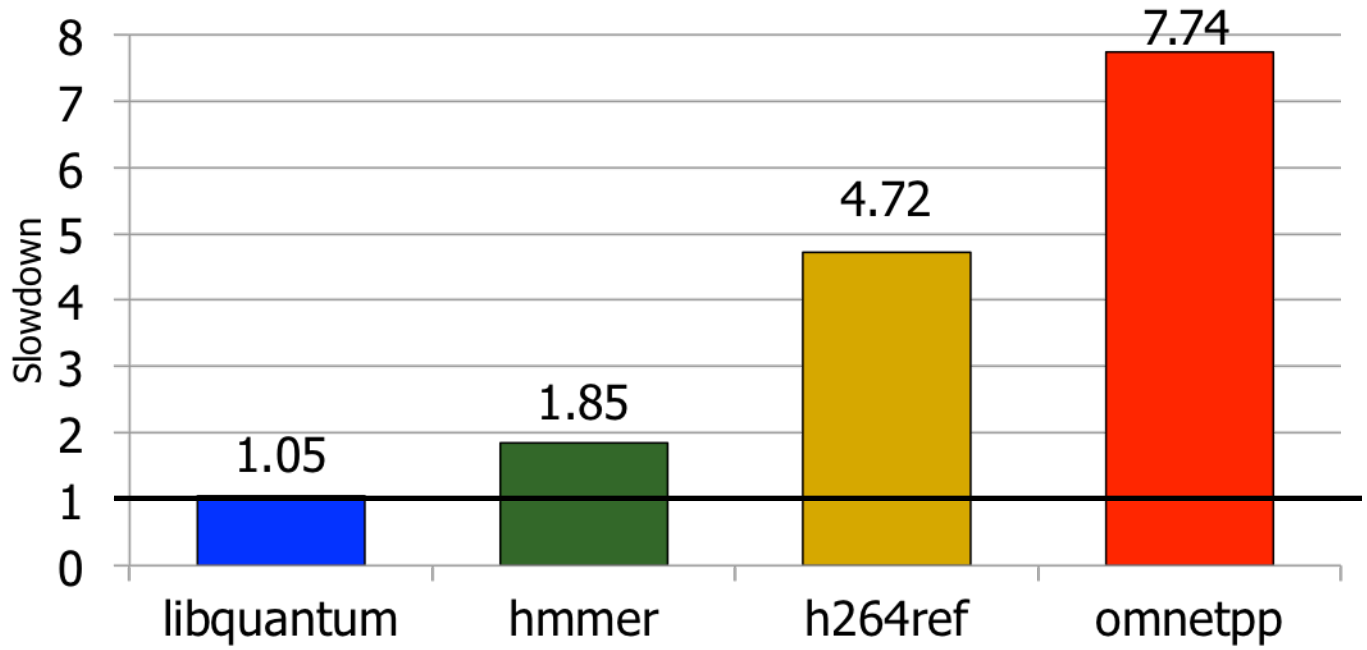
- Worst-case Execution Time Based Memory Scheduling for Real-Time Systems [Kim+ RTAS'14, JRTS'16]

Stall-Time Fair Memory Scheduling

Onur Mutlu and Thomas Moscibroda,
"Stall-Time Fair Memory Access Scheduling for Chip Multiprocessors"
40th International Symposium on Microarchitecture (***MICRO***),
pages 146-158, Chicago, IL, December 2007. Slides (ppt)

STFM Micro 2007 Talk

The Problem: Unfairness



- Vulnerable to denial of service (DoS)
- Unable to enforce priorities or SLAs
- Low system performance

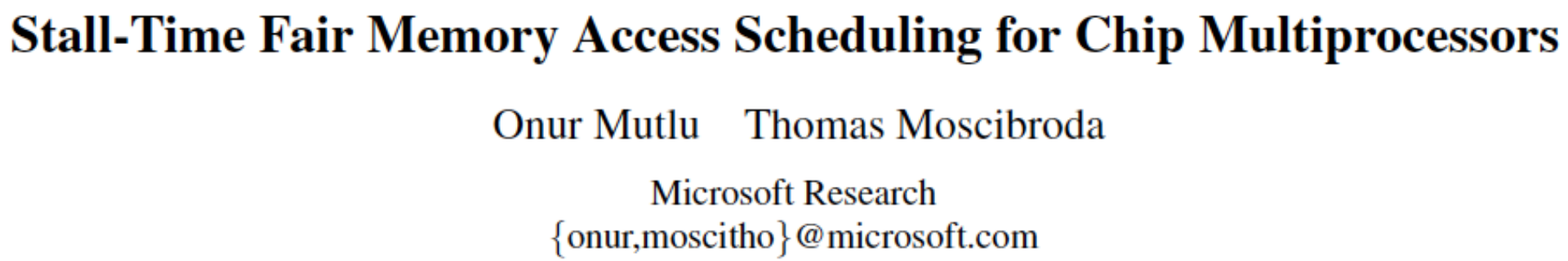
Uncontrollable, unpredictable system

STFM Scheduling Algorithm [MICRO' 07]

- For each thread, the DRAM controller
  - Tracks ST_{shared}
  - Estimates ST_{alone}
- Each cycle, the DRAM controller
  - Computes Slowdown = ST_{shared}/ST_{alone} for threads with legal requests
  - Computes unfairness = MAX Slowdown / MIN Slowdown
- If unfairness < α
  - Use DRAM throughput oriented scheduling policy
- If unfairness ≥ α
  - Use fairness-oriented scheduling policy
    - (1) requests from thread with MAX Slowdown first
    - (2) row-hit first , (3) oldest-first

More on STFM

- Onur Mutlu and Thomas Moscibroda,
  "Stall-Time Fair Memory Access Scheduling for Chip Multiprocessors"
  *Proceedings of the 40th International Symposium on Microarchitecture (**MICRO**)*, pages 146-158, Chicago, IL, December 2007. [Summary] [Slides (ppt)]



Stall-Time Fair Memory Access Scheduling for Chip Multiprocessors

Onur Mutlu Thomas Moscibroda

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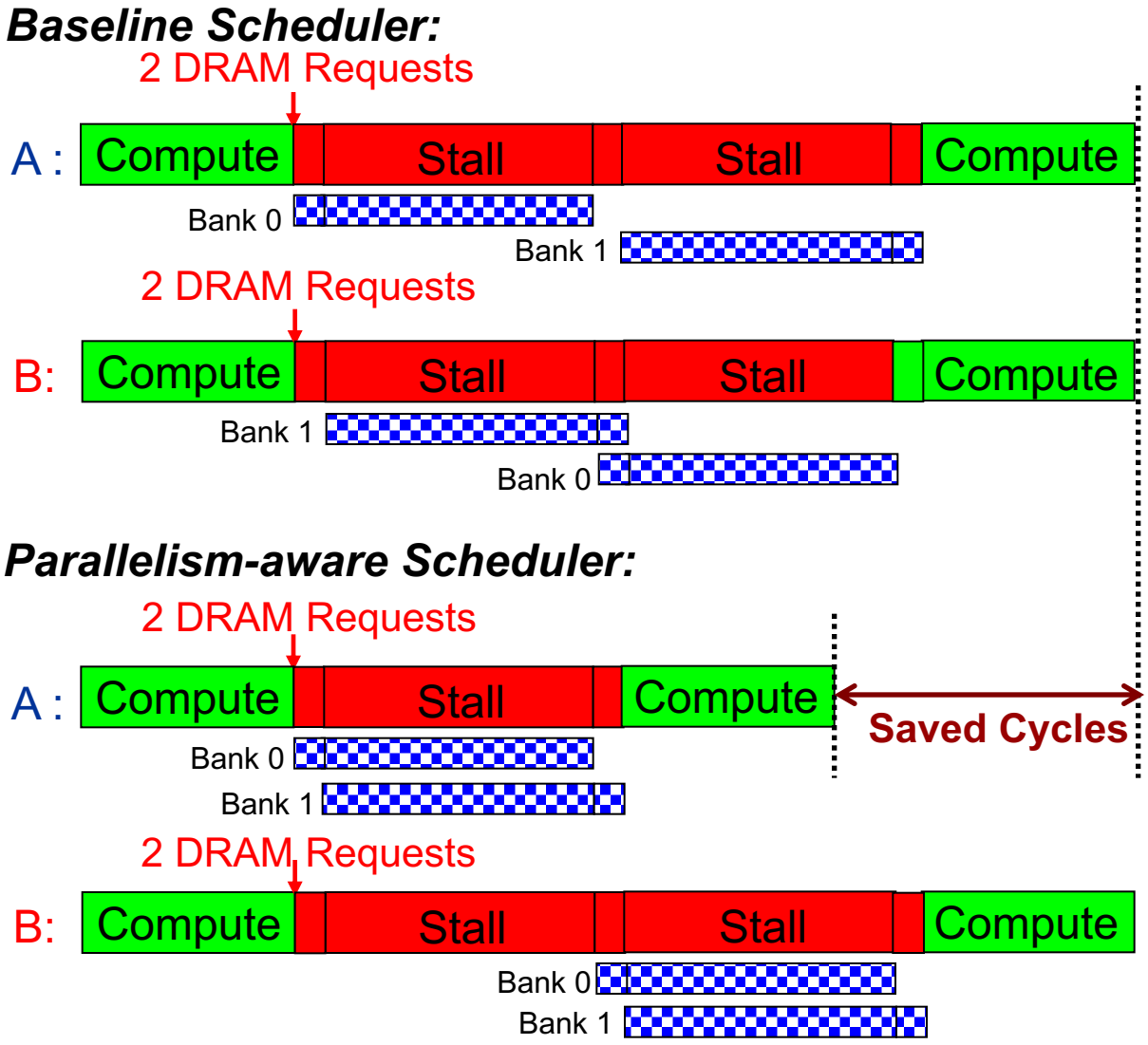
{onur,moscitho}@microsoft.com

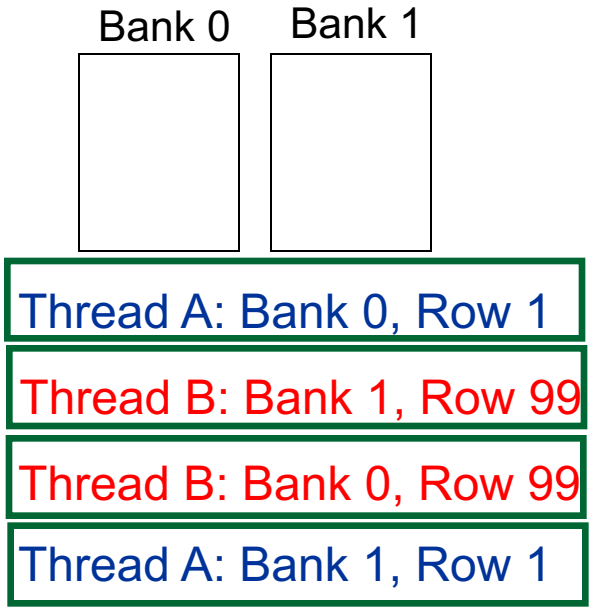
Parallelism-Aware Batch Scheduling

Onur Mutlu and Thomas Moscibroda,
"Parallelism-Aware Batch Scheduling: Enhancing both Performance and Fairness of Shared DRAM Systems"
35th International Symposium on Computer Architecture (***ISCA***),
pages 63-74, Beijing, China, June 2008. Slides (ppt)

PAR-BS ISCA 2008 Talk

Parallelism-Aware Scheduler

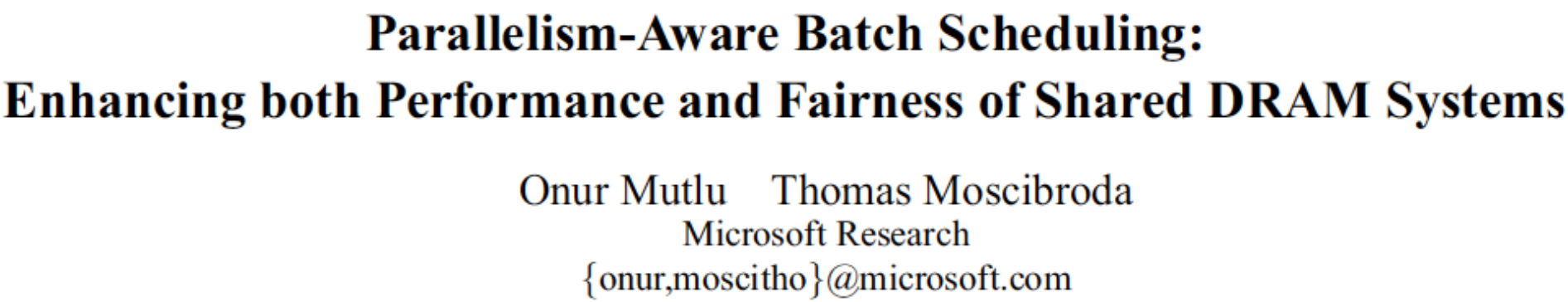




Average stall-time: ~1.5 bank access latencies

More on PAR-BS

- Onur Mutlu and Thomas Moscibroda,
  "Parallelism-Aware Batch Scheduling: Enhancing both Performance and Fairness of Shared DRAM Systems"
  *Proceedings of the 35th International Symposium on Computer Architecture (**ISCA**)*, pages 63-74, Beijing, China, June 2008.
  [Summary] [Slides (ppt)]
  One of the 12 computer architecture papers of 2008 selected as Top Picks by IEEE Micro.



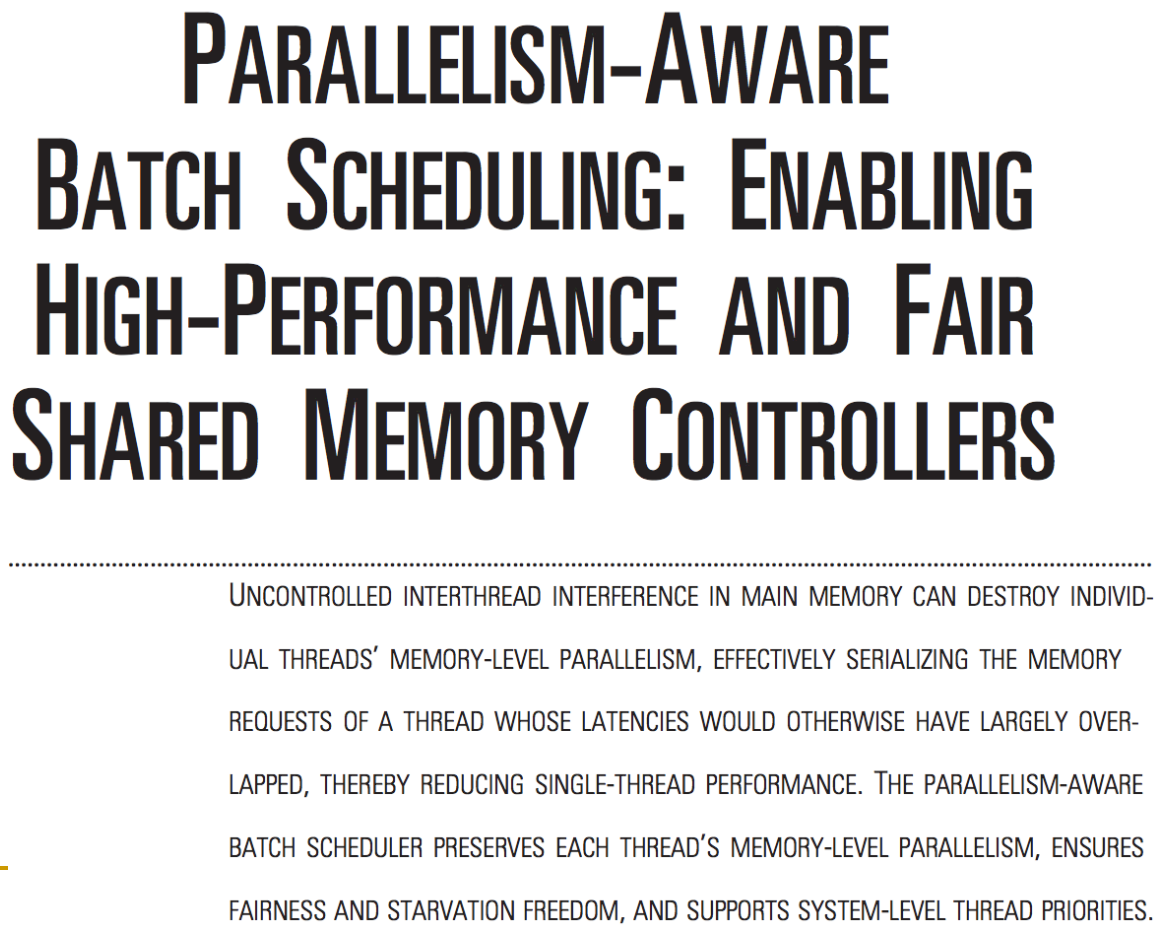
Parallelism-Aware Batch Scheduling:
Enhancing both Performance and Fairness of Shared DRAM Systems

Onur Mutlu Thomas Moscibroda
Microsoft Research
{onur,moscitho}@microsoft.com

http://www.youtube.com/watch?v=UB1kgYR-4V0

More on PAR-BS

- Onur Mutlu and Thomas Moscibroda,
  "Parallelism-Aware Batch Scheduling: Enabling High-Performance and Fair Memory Controllers"
  *IEEE Micro, Special Issue: Micro's Top Picks from 2008 Computer Architecture Conferences (**MICRO TOP PICKS**)*, Vol. 29, No. 1, pages 22-32, January/February 2009.



PARALLELISM-AWARE BATCH SCHEDULING: ENABLING HIGH-PERFORMANCE AND FAIR SHARED MEMORY CONTROLLERS

UNCONTROLLED INTERTHREAD INTERFERENCE IN MAIN MEMORY CAN DESTROY INDIVIDUAL THREADS' MEMORY-LEVEL PARALLELISM, EFFECTIVELY SERIALIZING THE MEMORY REQUESTS OF A THREAD WHOSE LATENCIES WOULD OTHERWISE HAVE LARGELY OVERLAPPED, THEREBY REDUCING SINGLE-THREAD PERFORMANCE. THE PARALLELISM-AWARE BATCH SCHEDULER PRESERVES EACH THREAD'S MEMORY-LEVEL PARALLELISM, ENSURES FAIRNESS AND STARVATION FREEDOM, AND SUPPORTS SYSTEM-LEVEL THREAD PRIORITIES.

ATLAS Memory Scheduler

Yoongu Kim, Dongsu Han, Onur Mutlu, and Mor Harchol-Balter,
"ATLAS: A Scalable and High-Performance Scheduling Algorithm for Multiple Memory Controllers"
16th International Symposium on High-Performance Computer Architecture (***HPCA***),
Bangalore, India, January 2010. Slides (pptx)

ATLAS HPCA 2010 Talk

ATLAS: Summary

- Goal: To maximize system performance

- Main idea: Prioritize the thread that has attained the least service from the memory controllers (Adaptive per-Thread Least Attained Service Scheduling)
  - Rank threads based on attained service in the past time interval(s)
  - Enforce thread ranking in the memory scheduler during the current interval

- Why it works: Prioritizes "light" (memory non-intensive) threads that are more likely to keep their cores busy

More on ATLAS Memory Scheduler

- Yoongu Kim, Dongsu Han, Onur Mutlu, and Mor Harchol-Balter, **"ATLAS: A Scalable and High-Performance Scheduling Algorithm for Multiple Memory Controllers"**
  *Proceedings of the 16th International Symposium on High-Performance Computer Architecture (**HPCA**)*, Bangalore, India, January 2010. Slides (pptx)
  Best paper session. One of the four papers nominated for the Best Paper Award by the Program Committee.

ATLAS: A Scalable and High-Performance Scheduling Algorithm for Multiple Memory Controllers

Yoongu Kim Dongsu Han Onur Mutlu Mor Harchol-Balter

Carnegie Mellon University

End of Recall: Memory Controllers and Shared Resources

Fundamental Interference Control Techniques

- Goal: to reduce/control inter-thread memory interference

1. Prioritization or request scheduling

2. Data mapping to banks/channels/ranks

3. Core/source throttling

4. Application/thread scheduling

More of these

Some of these

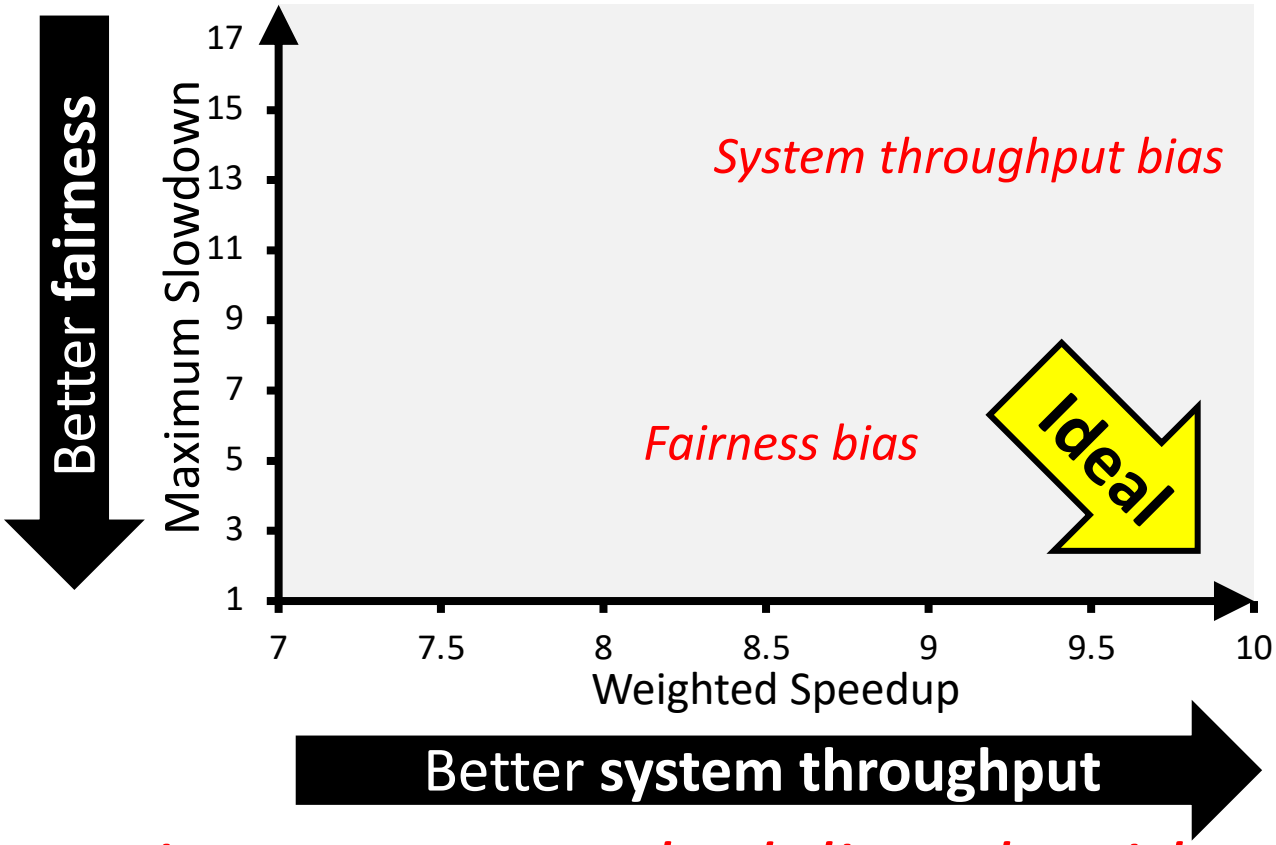
TCM:
Thread Cluster Memory Scheduling

Yoongu Kim, Michael Papamichael, Onur Mutlu, and Mor Harchol-Balter,
**"Thread Cluster Memory Scheduling:
Exploiting Differences in Memory Access Behavior"**
43rd International Symposium on Microarchitecture (***MICRO***),
pages 65-76, Atlanta, GA, December 2010. Slides (pptx) (pdf)

TCM Micro 2010 Talk

Previous Scheduling Algorithms are Biased

24 cores, 4 memory controllers, 96 workloads



No previous memory scheduling algorithm provides both the best fairness and system throughput

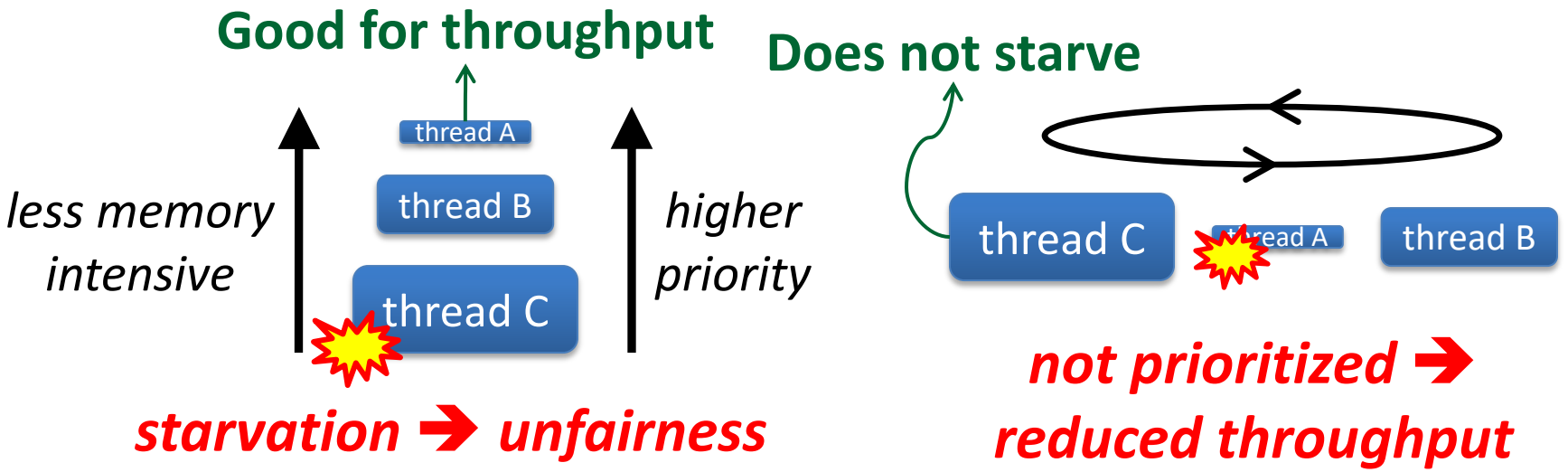
Throughput vs. Fairness

Throughput biased approach

Prioritize less memory-intensive threads

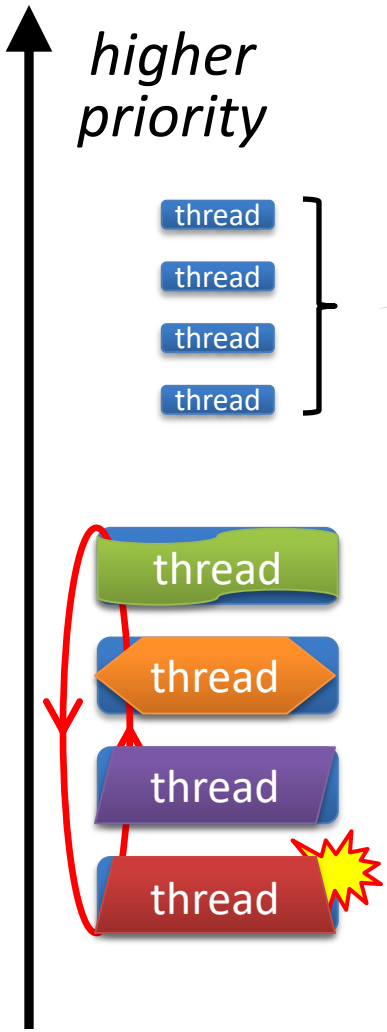
Fairness biased approach

Take turns accessing memory



Single policy for all threads is insufficient

Achieving the Best of Both Worlds



For Throughput

Prioritize memory-non-intensive threads

For Fairness

Unfairness caused by memory-intensive being prioritized over each other

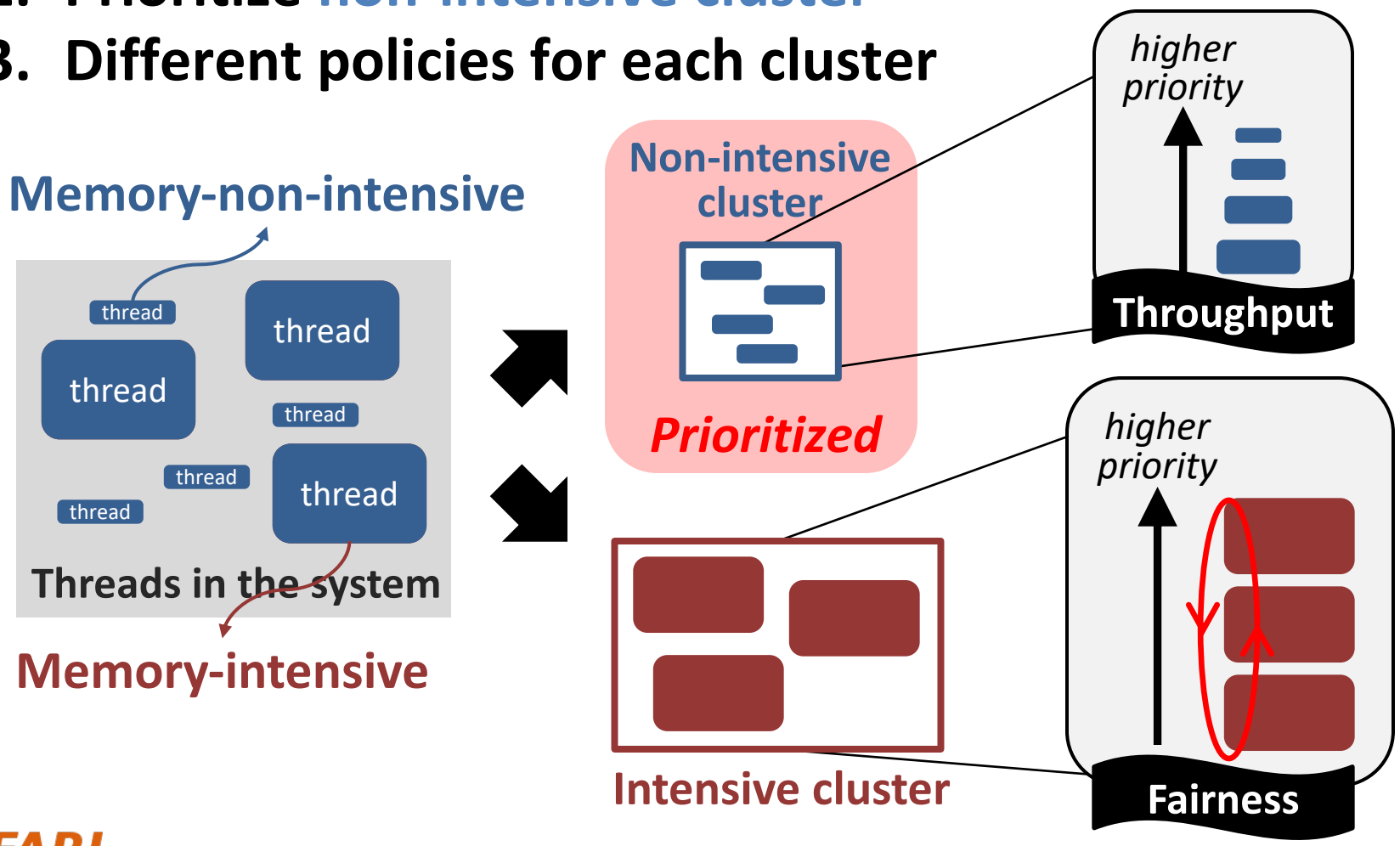
- Shuffle thread ranking

Memory-intensive threads have different vulnerability to interference

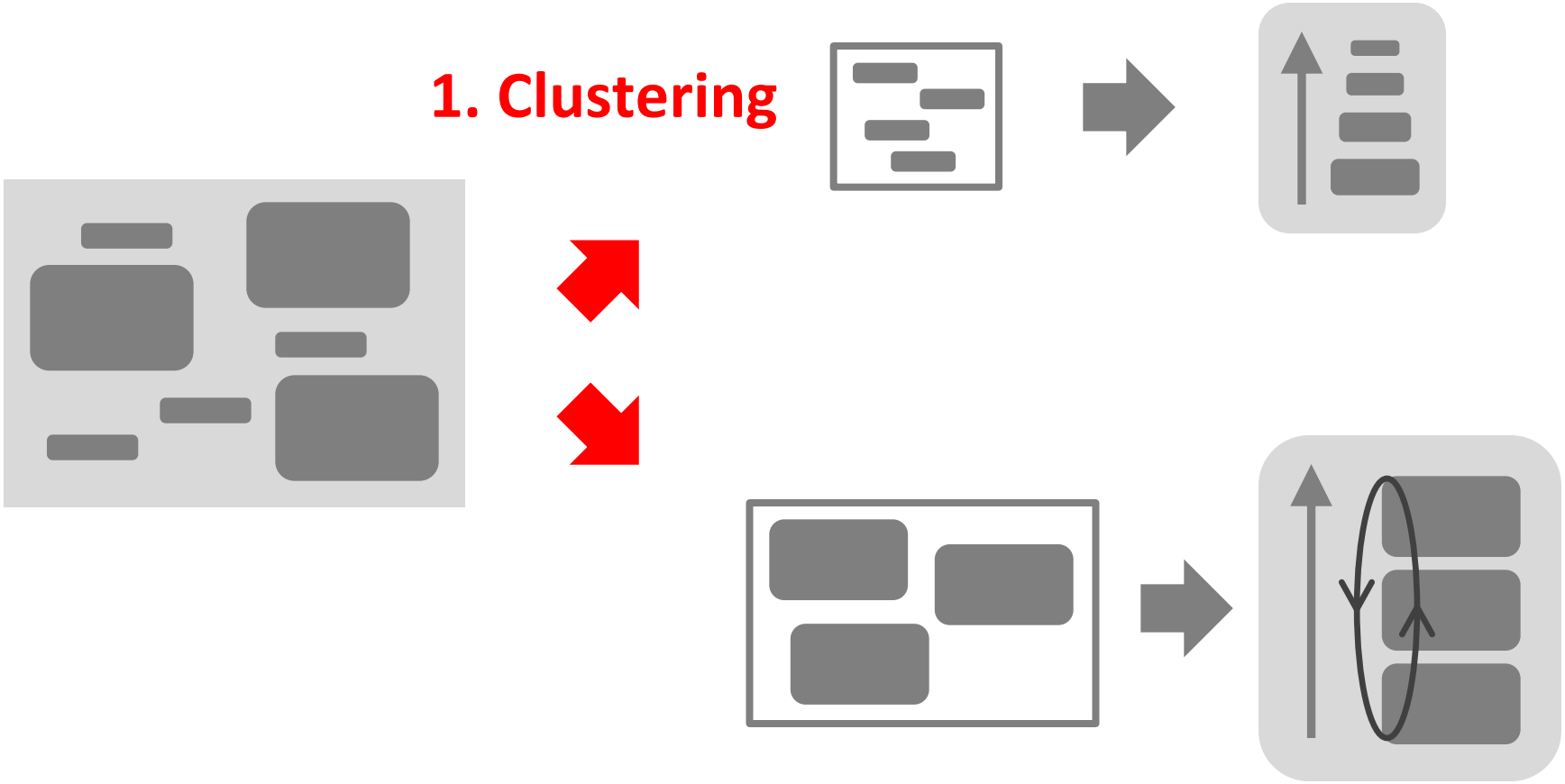
- Shuffle asymmetrically

Thread Cluster Memory Scheduling [Kim+ MICRO'10]

1. Group threads into two *clusters*
2. Prioritize non-intensive cluster
3. Different policies for each cluster

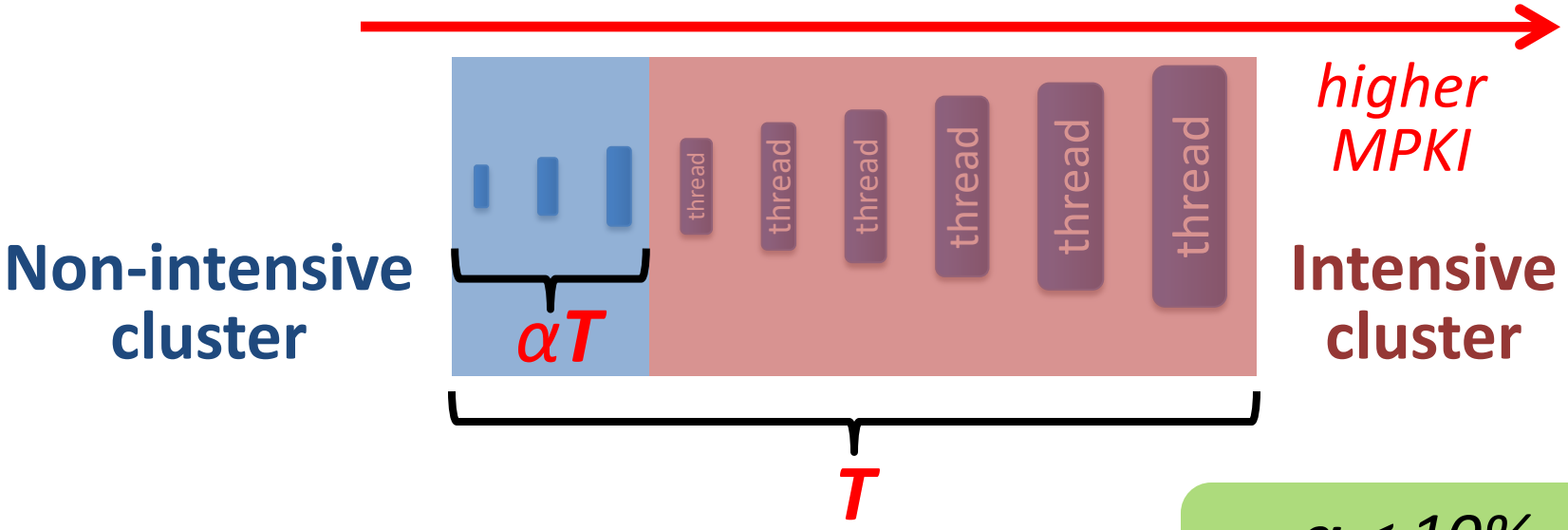


TCM Outline



Clustering Threads

Step1 Sort threads by **MPKI** (misses per kiloinstruction)

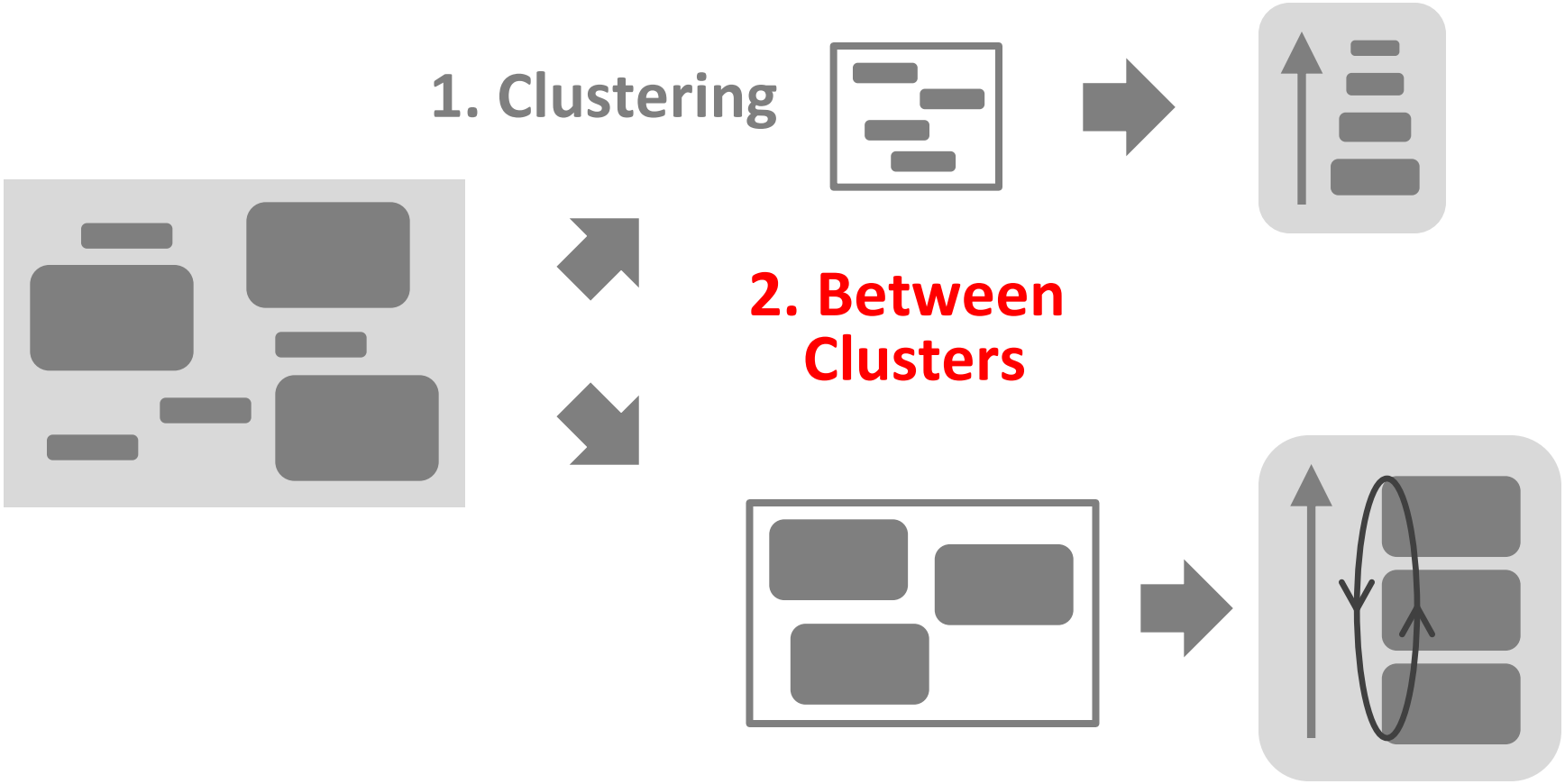


T = Total ***memory bandwidth usage***

α < 10%
ClusterThreshold

Step2 Memory bandwidth usage ***αT*** divides clusters

TCM Outline

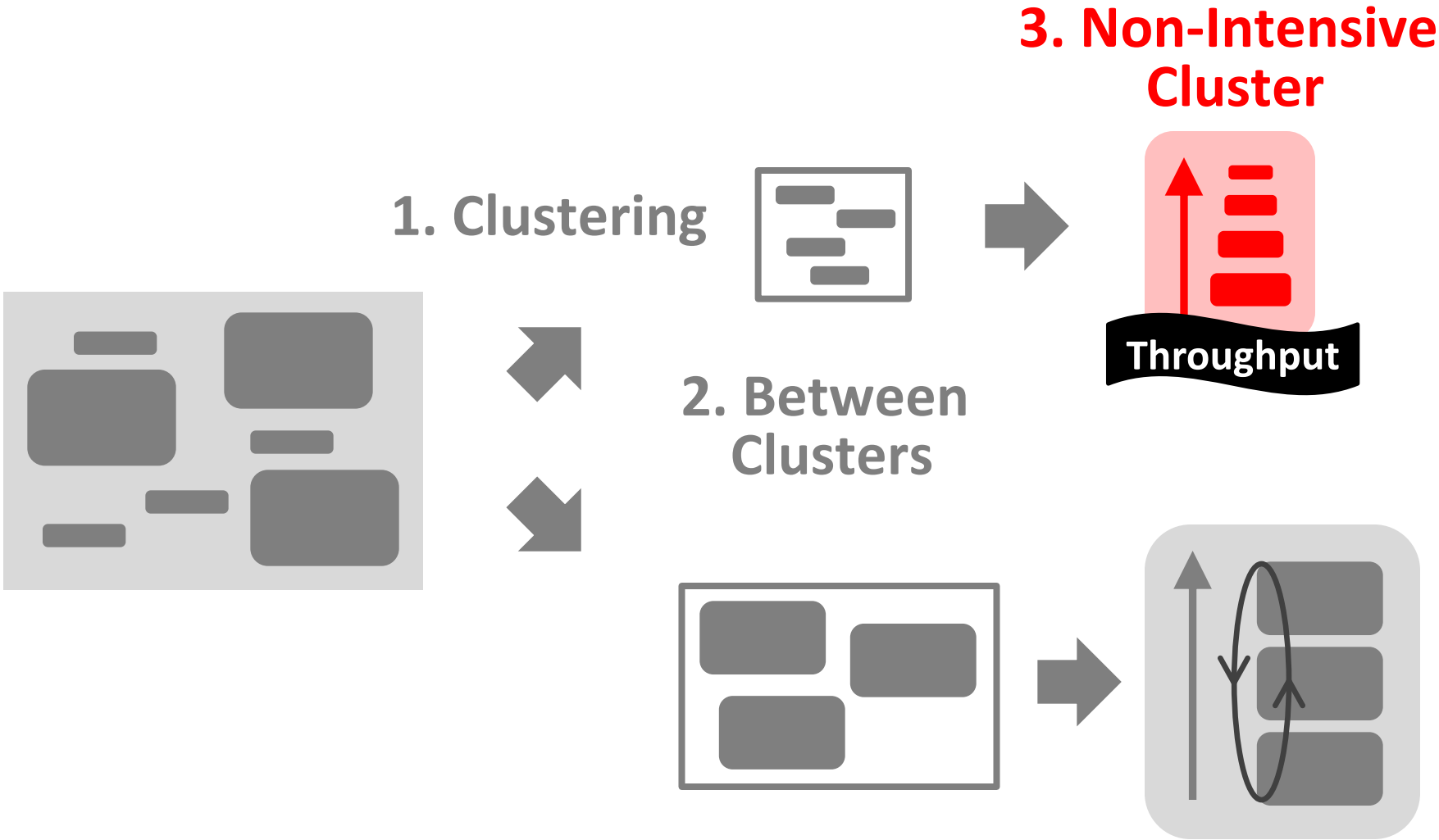


Prioritization Between Clusters

Prioritize non-intensive cluster

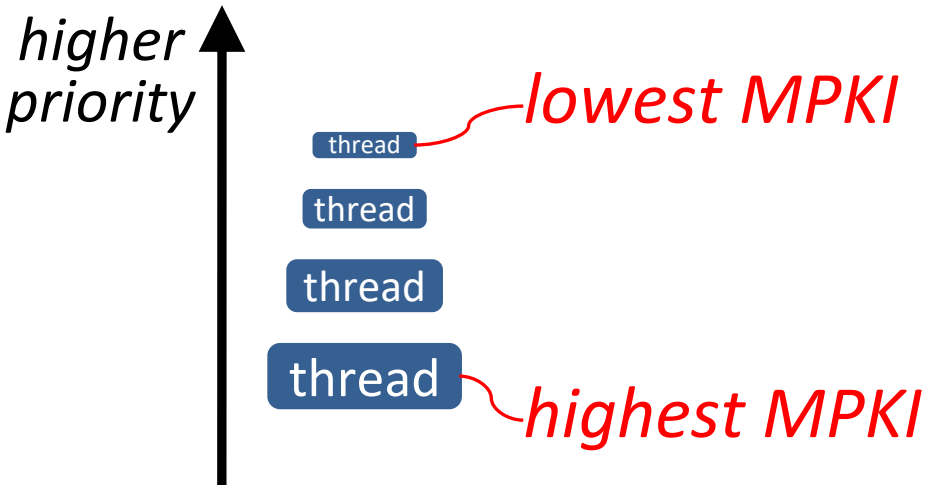
- **Increases system throughput**
  - Non-intensive threads have greater potential for making progress
- **Does not degrade fairness**
  - Non-intensive threads are "light"
  - Rarely interfere with intensive threads

TCM Outline


3. Non-Intensive Cluster
1. Clustering
Throughput
2. Between Clusters

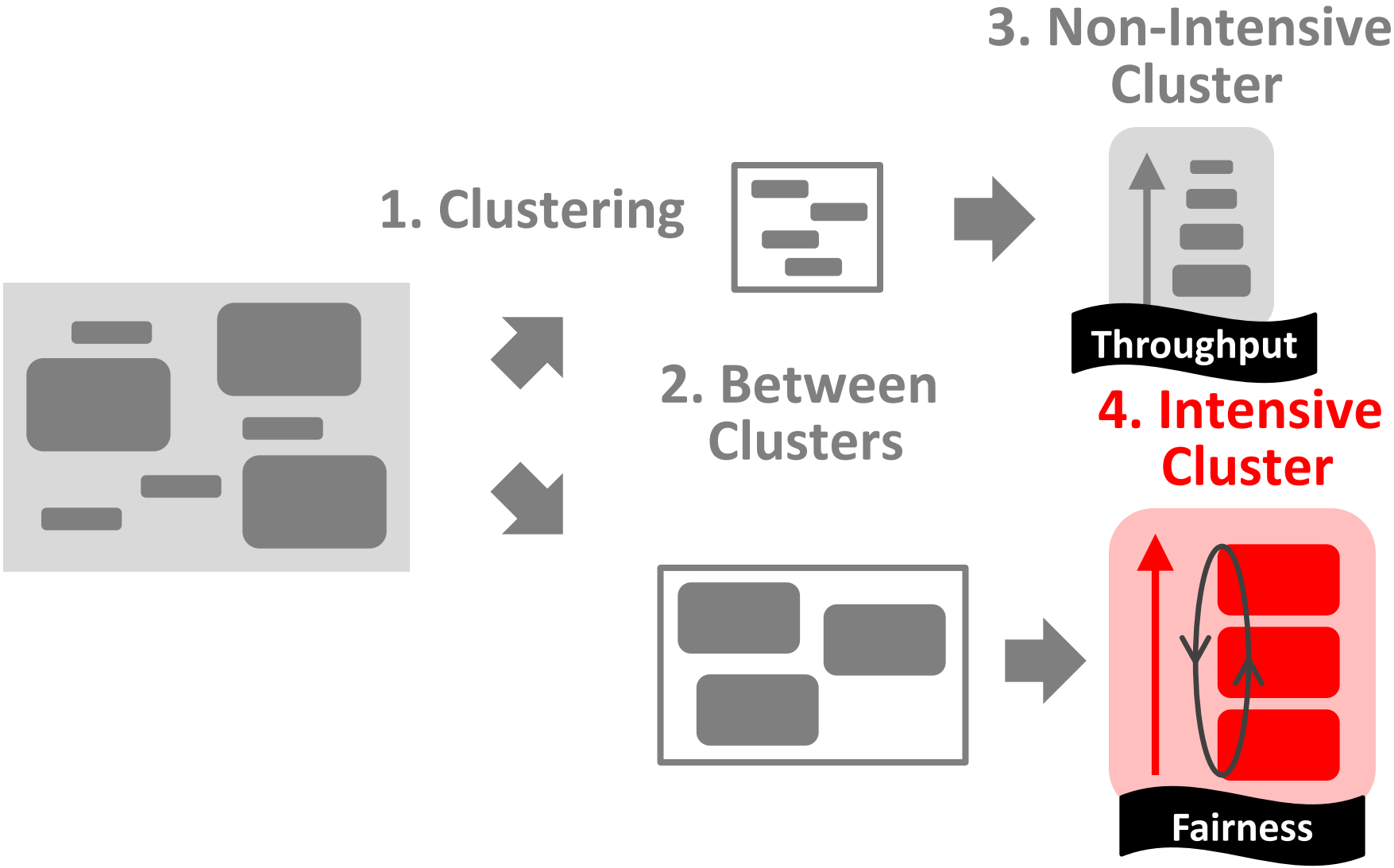
Non-Intensive Cluster

Prioritize threads according to MPKI



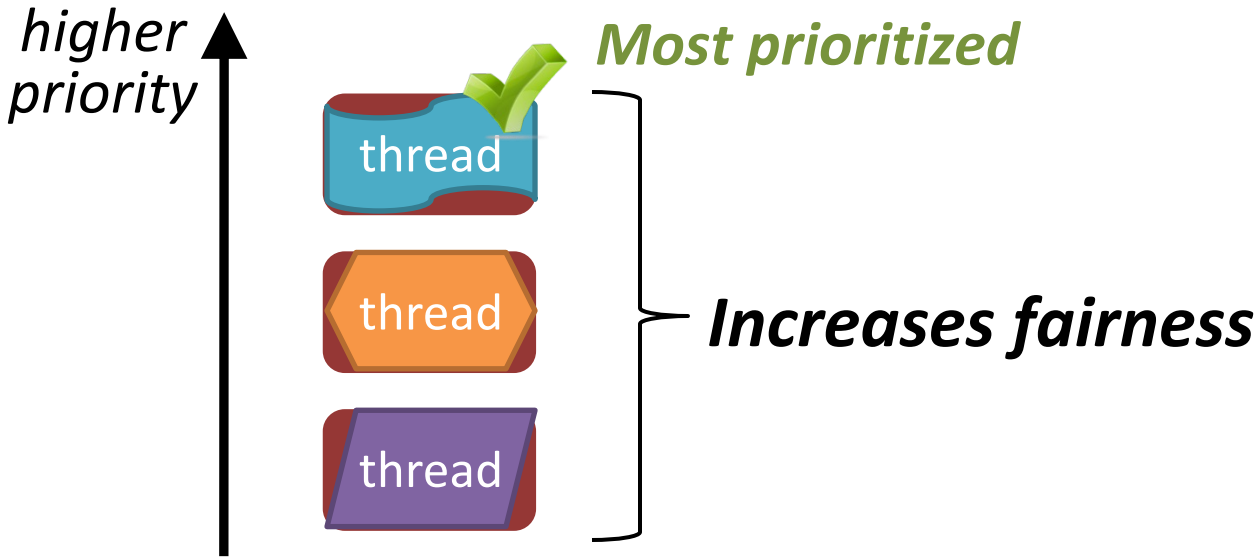
- **Increases system throughput**
  - Least intensive thread has the greatest potential for making progress in the processor

TCM Outline


3. Non-Intensive Cluster
1. Clustering
Throughput
2. Between Clusters
4. Intensive Cluster
Fairness

Intensive Cluster

Periodically shuffle the priority of threads



- Is treating all threads equally good enough?
- ***BUT:*** *Equal turns ≠ Same slowdown*

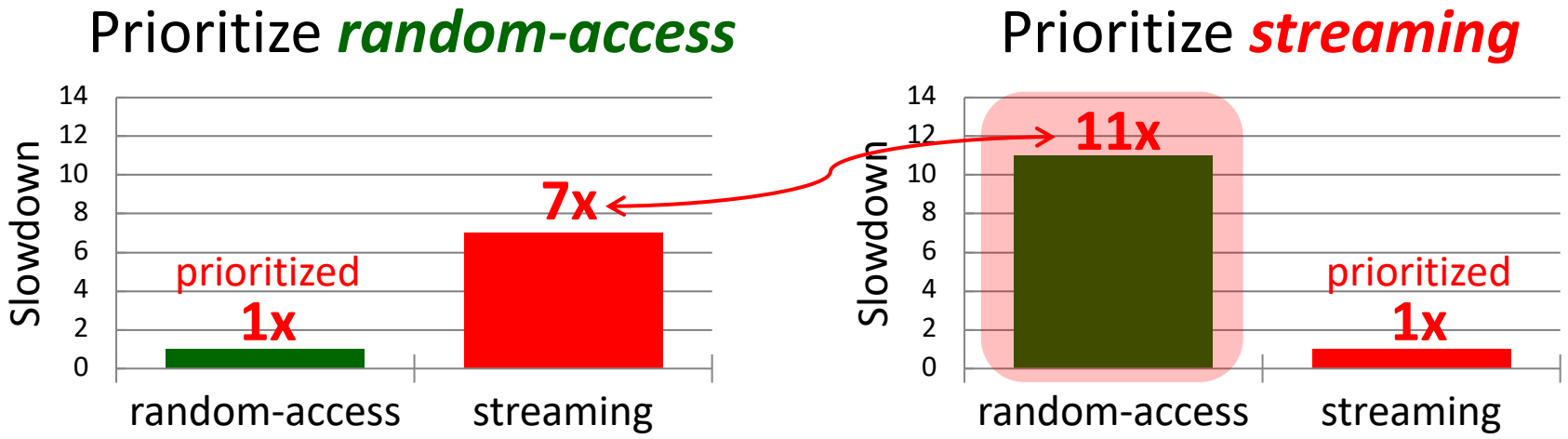
Case Study: A Tale of Two Threads

Case Study: Two intensive threads contending

1. random-access

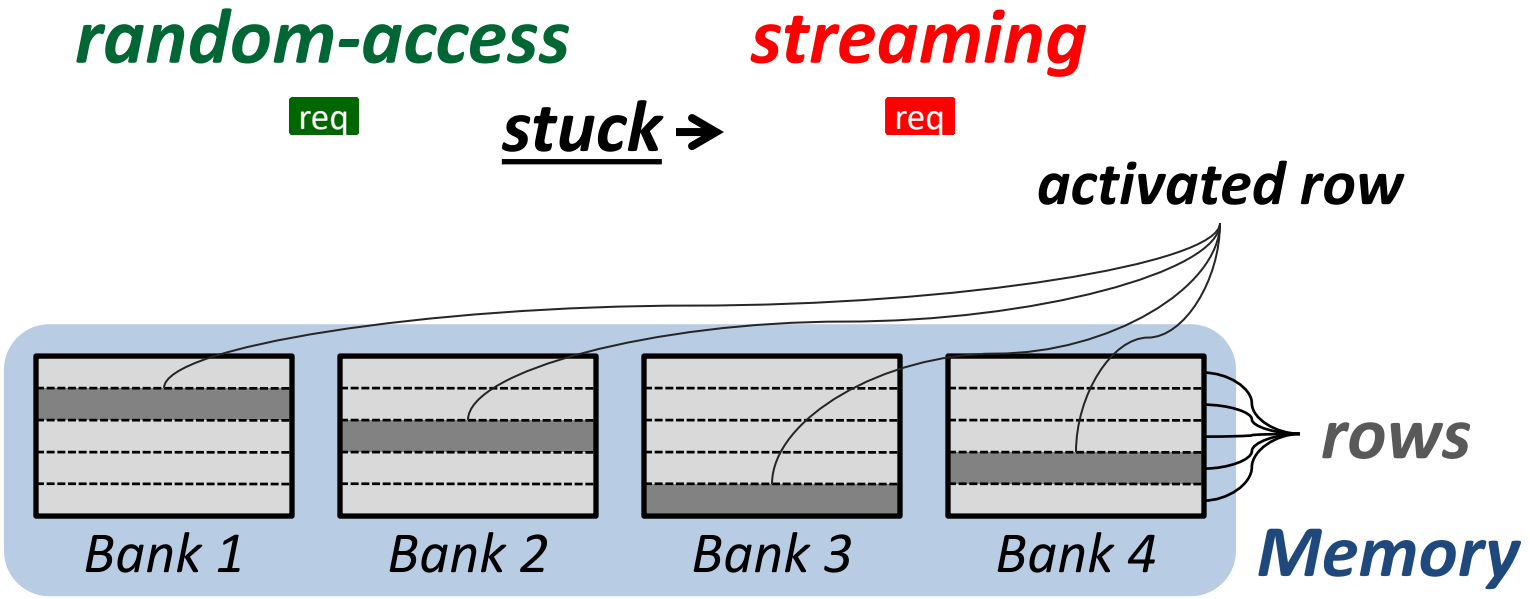
2. streaming

} ***Which is slowed down more easily?***



random-access thread is more easily slowed down

Why are Threads Different?

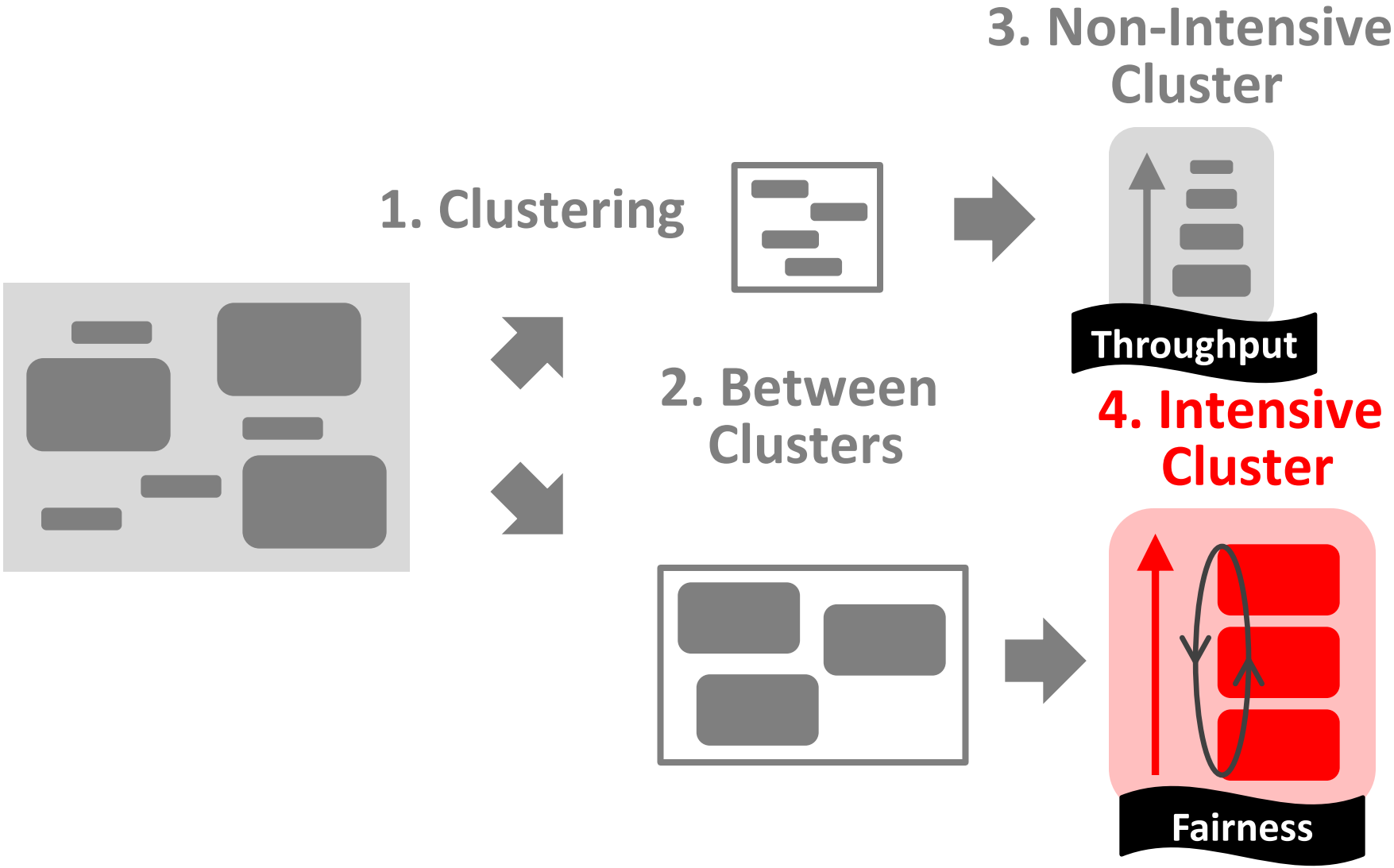


- All requests parallel
- High **bank-level parallelism**

- All requests → Same row
- High **row-buffer locality**

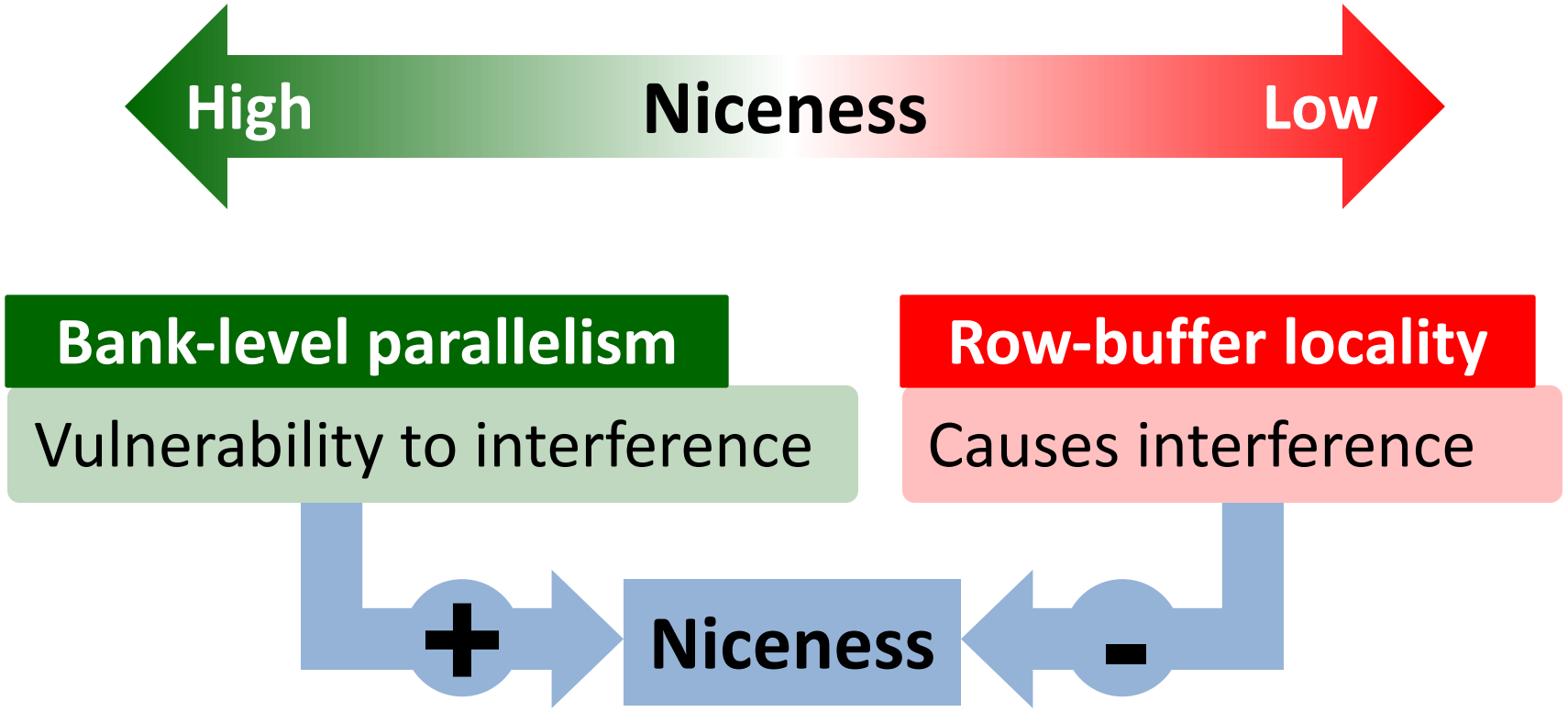
Vulnerable to interference

TCM Outline

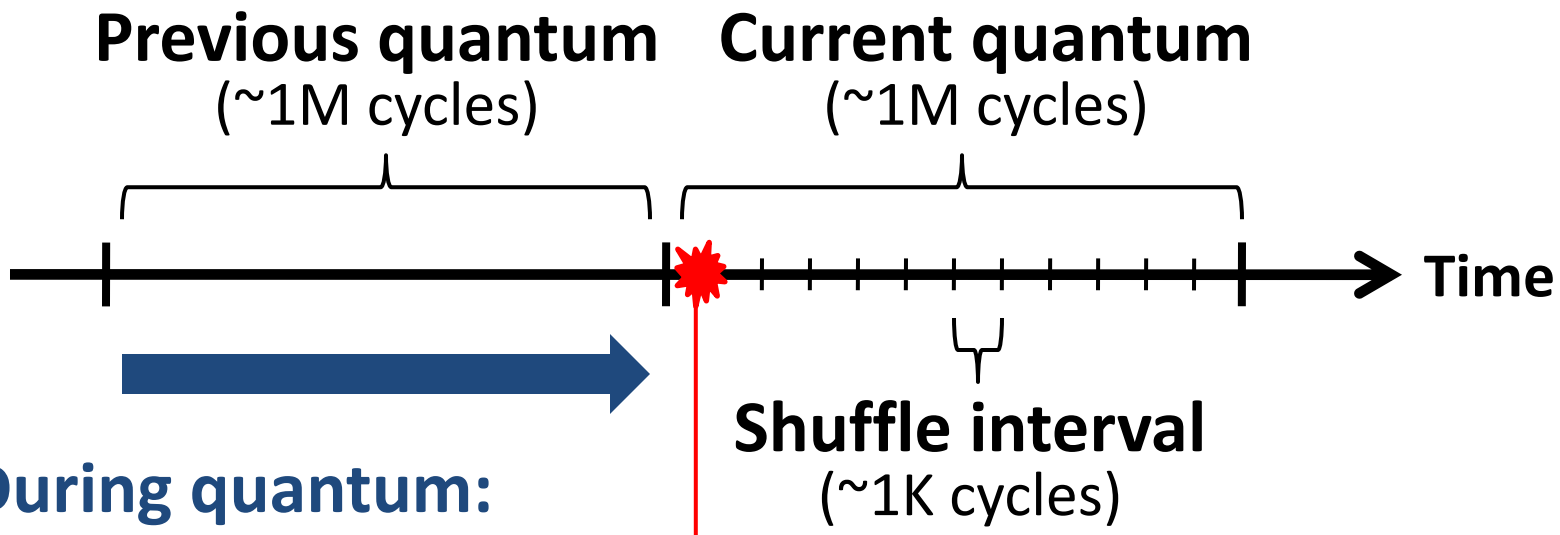

3. Non-Intensive Cluster
1. Clustering
Throughput
2. Between Clusters
4. Intensive Cluster
Fairness

Niceness

How to quantify difference between threads?



TCM: Quantum-Based Operation



During quantum:

- Monitor thread behavior
  1. Memory intensity
  2. Bank-level parallelism
  3. Row-buffer locality

Beginning of quantum:

- Perform clustering
- Compute niceness of intensive threads

TCM: Scheduling Algorithm

1. ***Highest-rank***: Requests from higher ranked threads prioritized
   - **Non-Intensive** cluster **>** **Intensive** cluster
   - **Non-Intensive** cluster: lower intensity ➔ higher rank
   - **Intensive** cluster: rank shuffling

2. ***Row-hit***: Row-buffer hit requests are prioritized

3. ***Oldest***: Older requests are prioritized

TCM: Implementation Cost

Required storage at memory controller *(24 cores)*

Thread memory behavior	Storage
MPKI	~0.2kb
Bank-level parallelism	~0.6kb
Row-buffer locality	~2.9kb
Total	**< 4kbits**

- No computation is on the critical path

Previous Work

FRFCFS [Rixner et al., ISCA00]: Prioritizes row-buffer hits

- Thread-oblivious ➔ Low throughput & Low fairness

STFM [Mutlu et al., MICRO07]: Equalizes thread slowdowns

- Non-intensive threads not prioritized ➔ Low throughput

PAR-BS [Mutlu et al., ISCA08]: Prioritizes oldest batch of requests while preserving bank-level parallelism

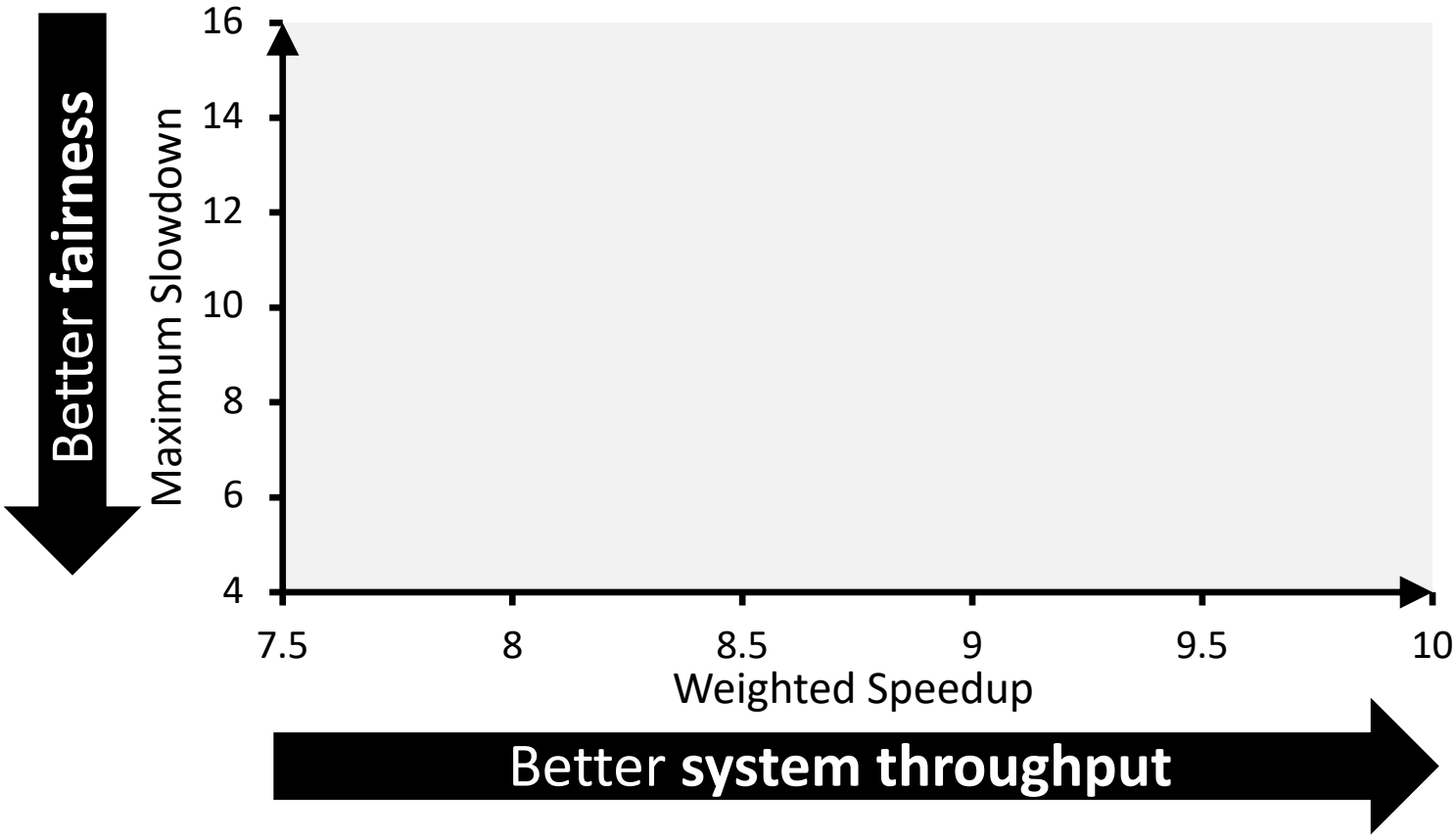
- Non-intensive threads not always prioritized ➔ Low throughput

ATLAS [Kim et al., HPCA10]: Prioritizes threads with less memory service

- Most intensive thread starves ➔ Low fairness

TCM: Throughput and Fairness

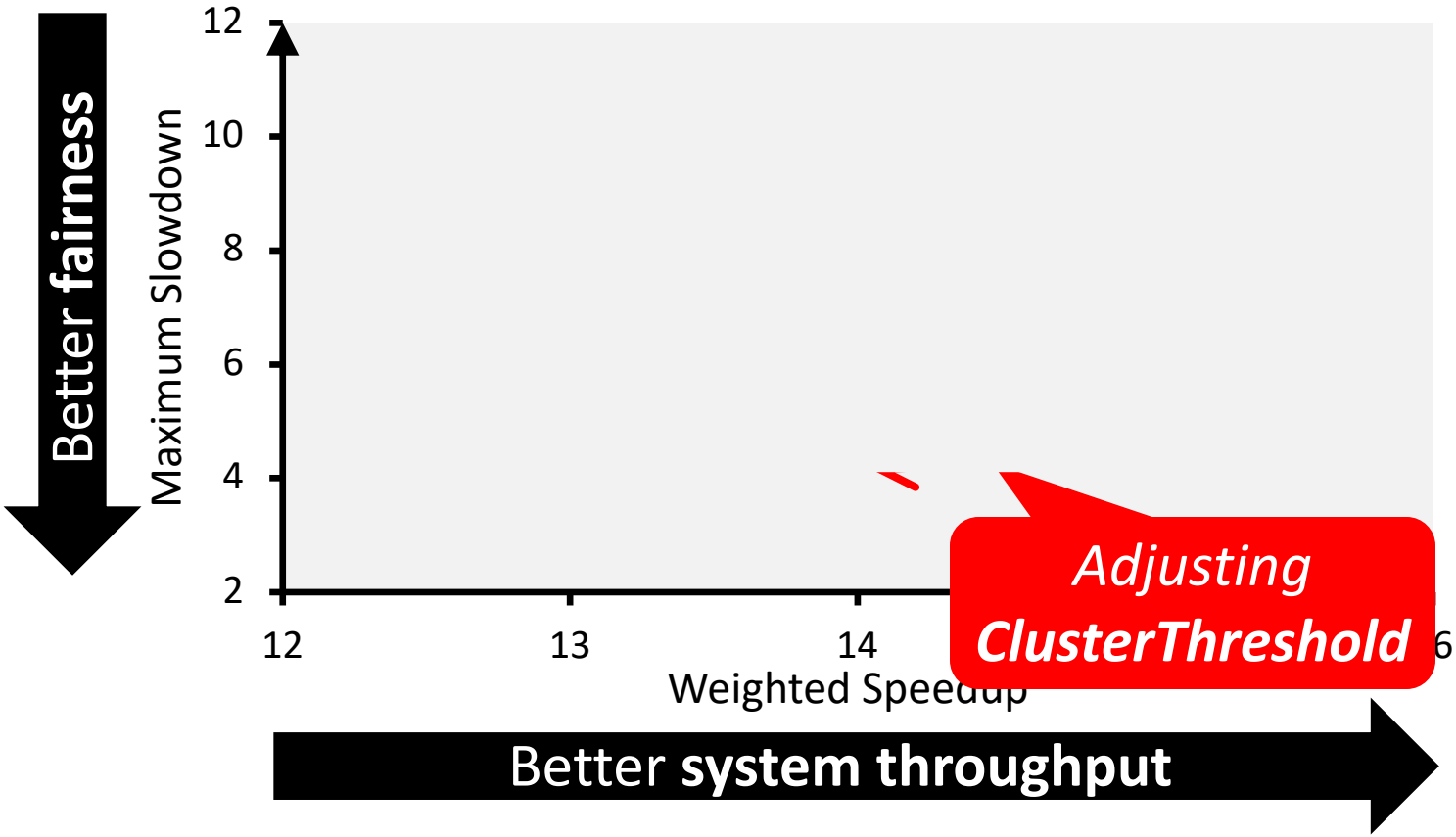
24 cores, 4 memory controllers, 96 workloads



TCM, a heterogeneous scheduling policy, provides best fairness and system throughput

TCM: Fairness-Throughput Tradeoff

When configuration parameter is varied…



TCM allows robust fairness-throughput tradeoff

Operating System Support

- ***ClusterThreshold*** is a tunable knob
  - OS can trade off between fairness and throughput

- Enforcing thread weights
  - OS assigns weights to threads
  - TCM enforces thread weights within each cluster

Conclusion

- No previous memory scheduling algorithm provides both high ***system throughput*** and ***fairness***
  - **Problem:** They use a single policy for all threads

- TCM groups threads into two ***clusters***
  1. Prioritize ***non-intensive*** cluster → throughput
  2. Shuffle priorities in ***intensive*** cluster → fairness
  3. Shuffling should favor ***nice*** threads → fairness

- *TCM provides the best system throughput and fairness*

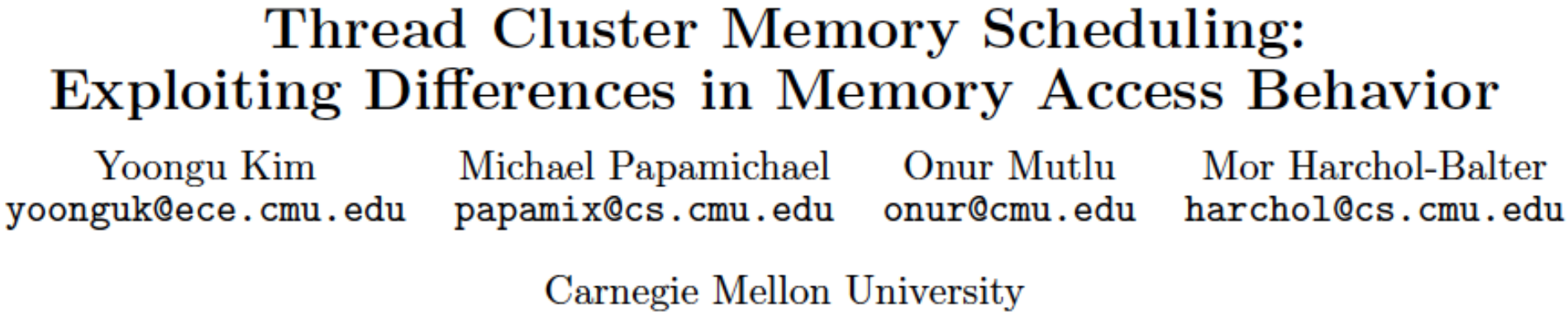
TCM Pros and Cons

- Upsides:
  - Provides both high fairness and high performance
  - Caters to the needs for different types of threads (latency vs. bandwidth sensitive)
  - (Relatively) simple

- Downsides:
  - Scalability to large buffer sizes?
  - Robustness of clustering and shuffling algorithms?
  - Ranking is still too complex?

More on TCM

- Yoongu Kim, Michael Papamichael, Onur Mutlu, and Mor Harchol-Balter, **"Thread Cluster Memory Scheduling: Exploiting Differences in Memory Access Behavior"**
  *Proceedings of the 43rd International Symposium on Microarchitecture (**MICRO**)*, pages 65-76, Atlanta, GA, December 2010. Slides (pptx) (pdf)
  One of the 11 computer architecture papers of 2010 selected as Top Picks by IEEE Micro.



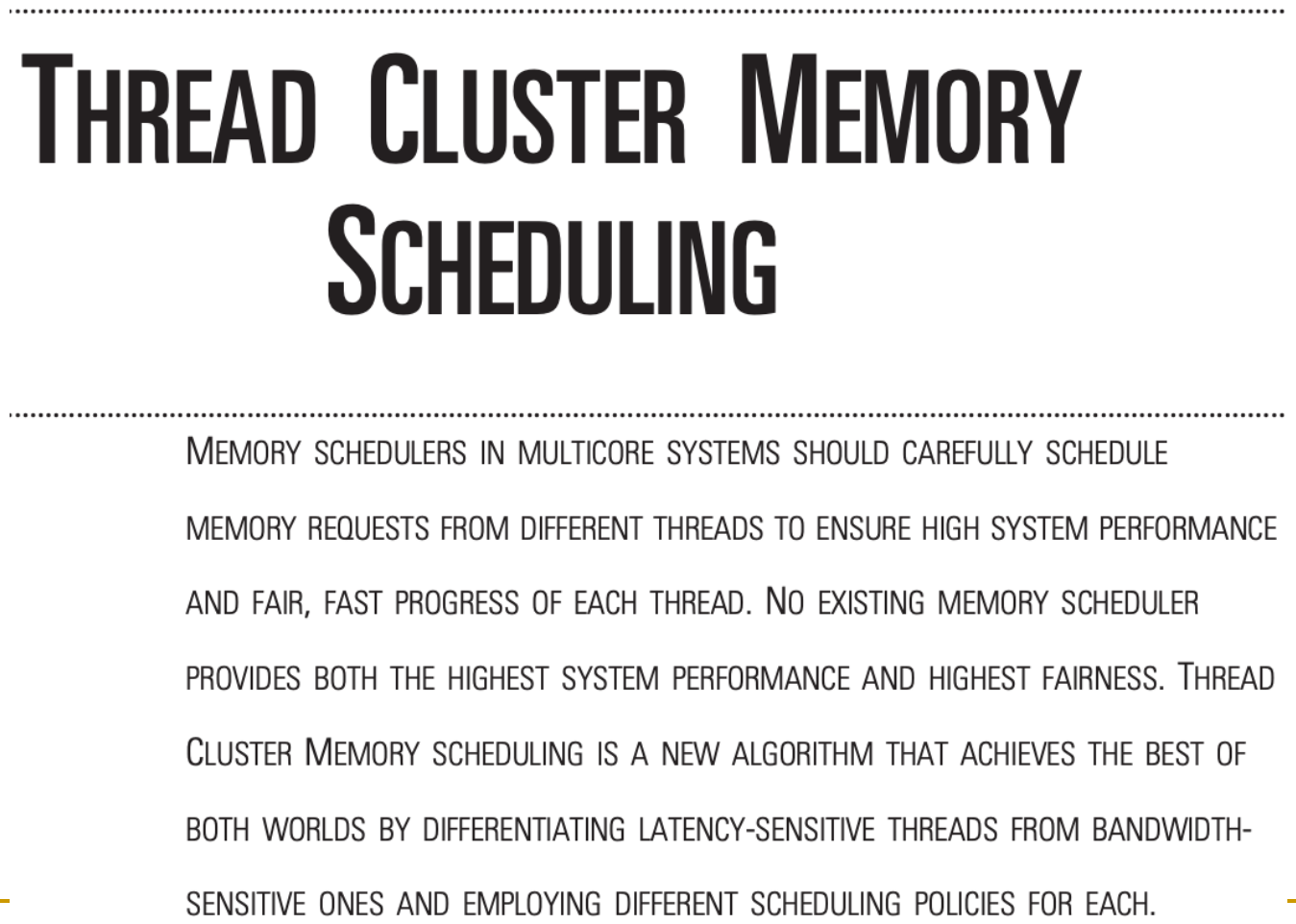
Thread Cluster Memory Scheduling:
Exploiting Differences in Memory Access Behavior

Yoongu Kim yoonguk@ece.cmu.edu
Michael Papamichael papamix@cs.cmu.edu
Onur Mutlu onur@cmu.edu
Mor Harchol-Balter harchol@cs.cmu.edu

Carnegie Mellon University

More on TCM

- Yoongu Kim, Michael Papamichael, Onur Mutlu, and Mor Harchol-Balter, **"Thread Cluster Memory Scheduling"**
  *IEEE Micro, Special Issue: Micro's Top Picks from 2010 Computer Architecture Conferences (**MICRO TOP PICKS**)*, Vol. 31, No. 1, pages 78-89, January/February 2011.



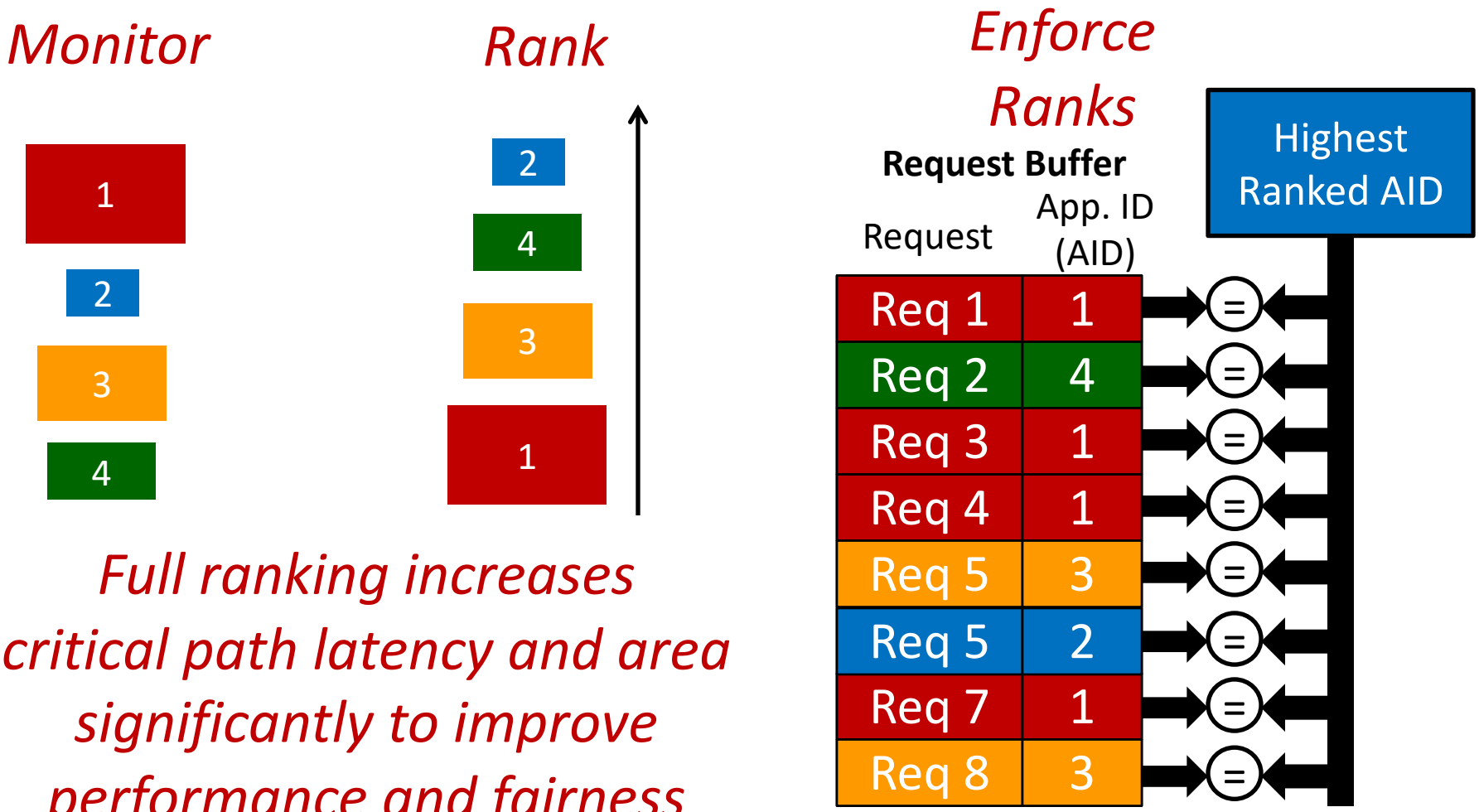
THREAD CLUSTER MEMORY SCHEDULING

MEMORY SCHEDULERS IN MULTICORE SYSTEMS SHOULD CAREFULLY SCHEDULE MEMORY REQUESTS FROM DIFFERENT THREADS TO ENSURE HIGH SYSTEM PERFORMANCE AND FAIR, FAST PROGRESS OF EACH THREAD. NO EXISTING MEMORY SCHEDULER PROVIDES BOTH THE HIGHEST SYSTEM PERFORMANCE AND HIGHEST FAIRNESS. THREAD CLUSTER MEMORY SCHEDULING IS A NEW ALGORITHM THAT ACHIEVES THE BEST OF BOTH WORLDS BY DIFFERENTIATING LATENCY-SENSITIVE THREADS FROM BANDWIDTH-SENSITIVE ONES AND EMPLOYING DIFFERENT SCHEDULING POLICIES FOR EACH.

The Blacklisting Memory Scheduler

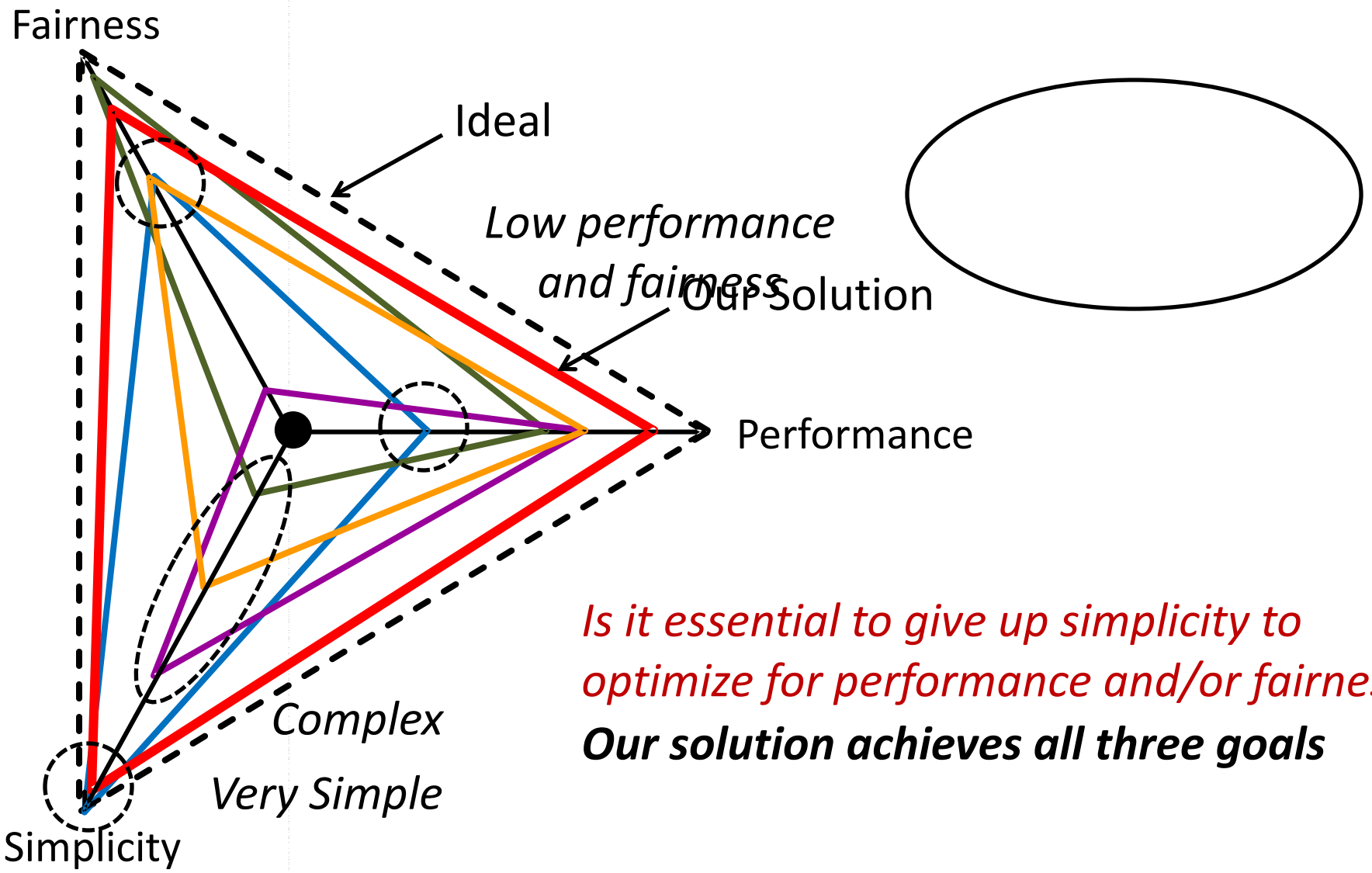
Lavanya Subramanian, Donghyuk Lee, Vivek Seshadri, Harsha Rastogi, and Onur Mutlu,
"The Blacklisting Memory Scheduler: Achieving High Performance and Fairness at Low Cost"
*Proceedings of the 32nd IEEE International Conference on Computer Design (**ICCD**)*,
Seoul, South Korea, October 2014. [Slides (pptx) (pdf)]

Tackling Inter-Application Interference: Application-aware Memory Scheduling



Full ranking increases critical path latency and area significantly to improve performance and fairness

Performance vs. Fairness vs. Simplicity

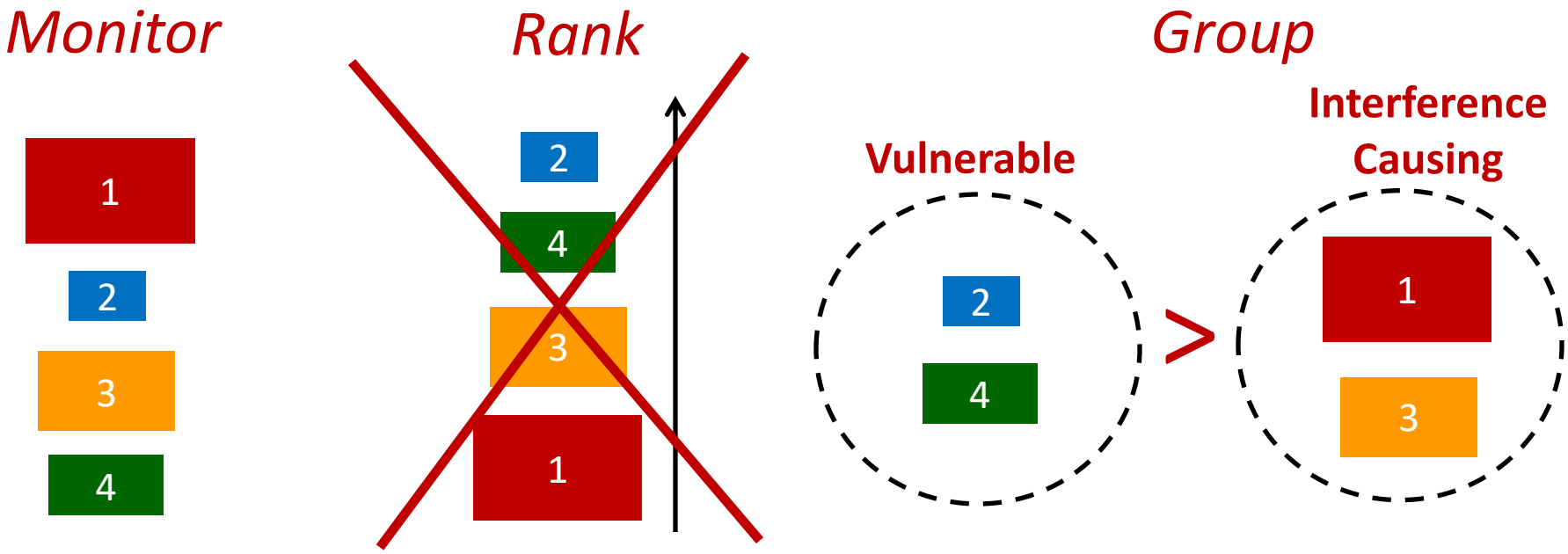


Is it essential to give up simplicity to optimize for performance and/or fairness?

Our solution achieves all three goals

Key Observation 1: Group Rather Than Rank

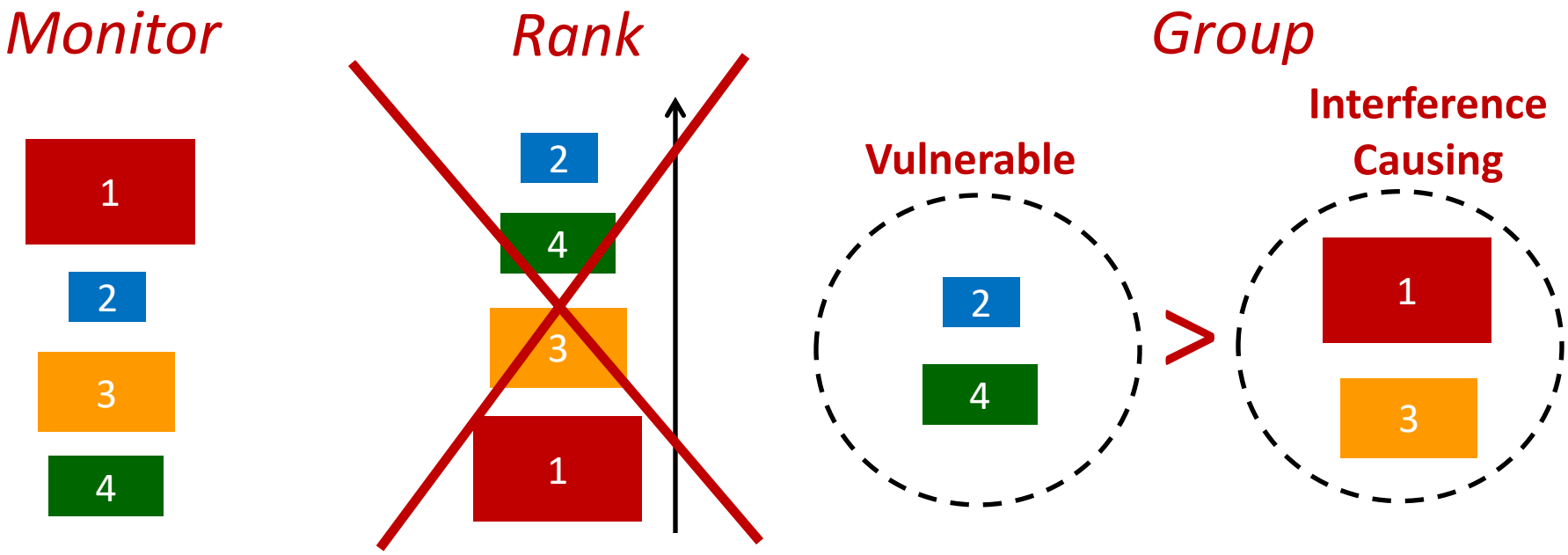
Observation 1: Sufficient to separate applications into two groups, rather than do full ranking



Benefit 2: Lower slowdowns than ranking

Key Observation 1: Group Rather Than Rank

Observation 1: *Sufficient to separate applications into two groups, rather than do full ranking*



How to classify applications into groups?

Key Observation 2

Observation 2: Serving a large number of consecutive requests from an application causes interference

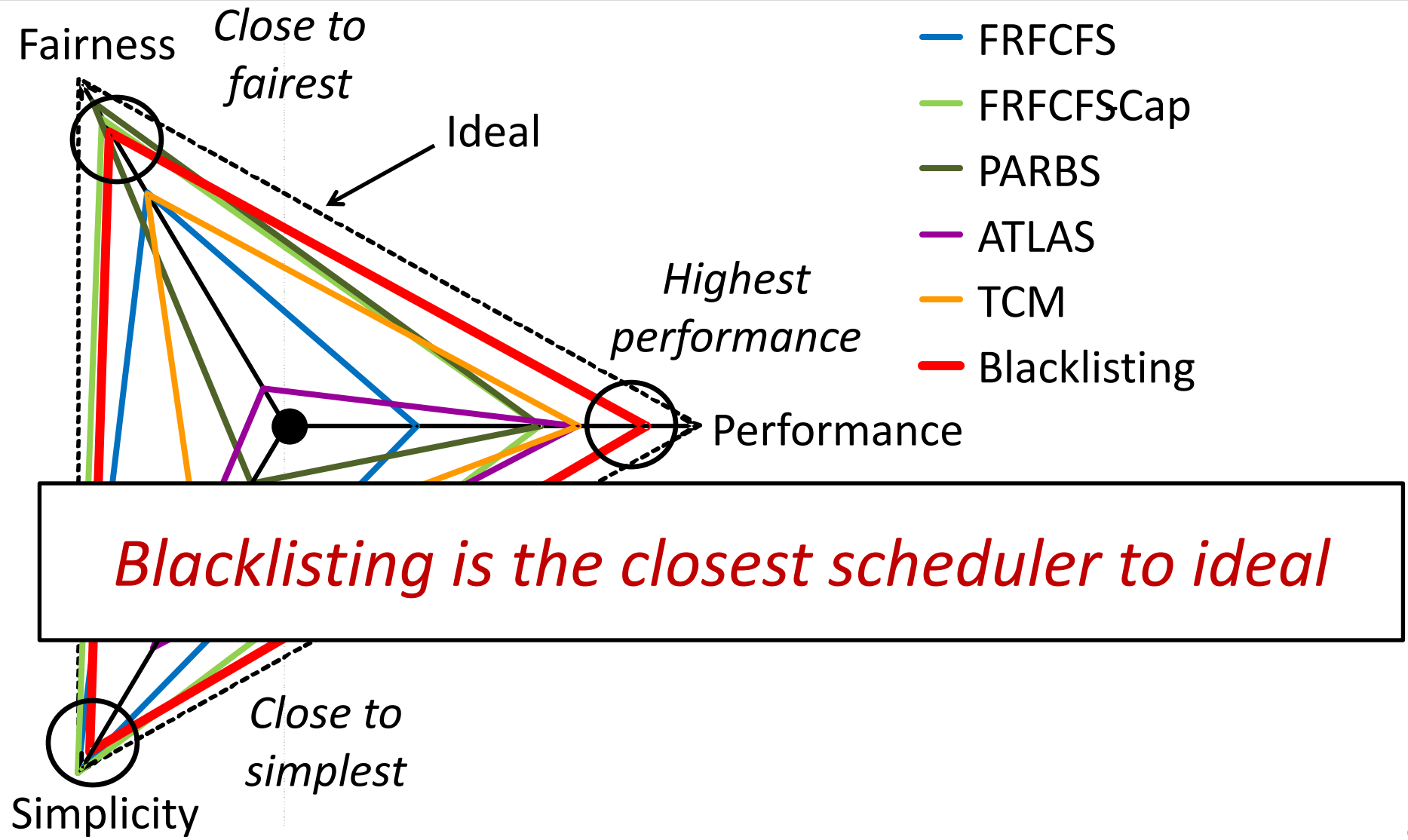
Basic Idea:

- *Group* applications with a large number of consecutive requests as *interference-causing* → *Blacklisting*
- *Deprioritize* blacklisted applications
- *Clear* blacklist periodically (1000s of cycles)

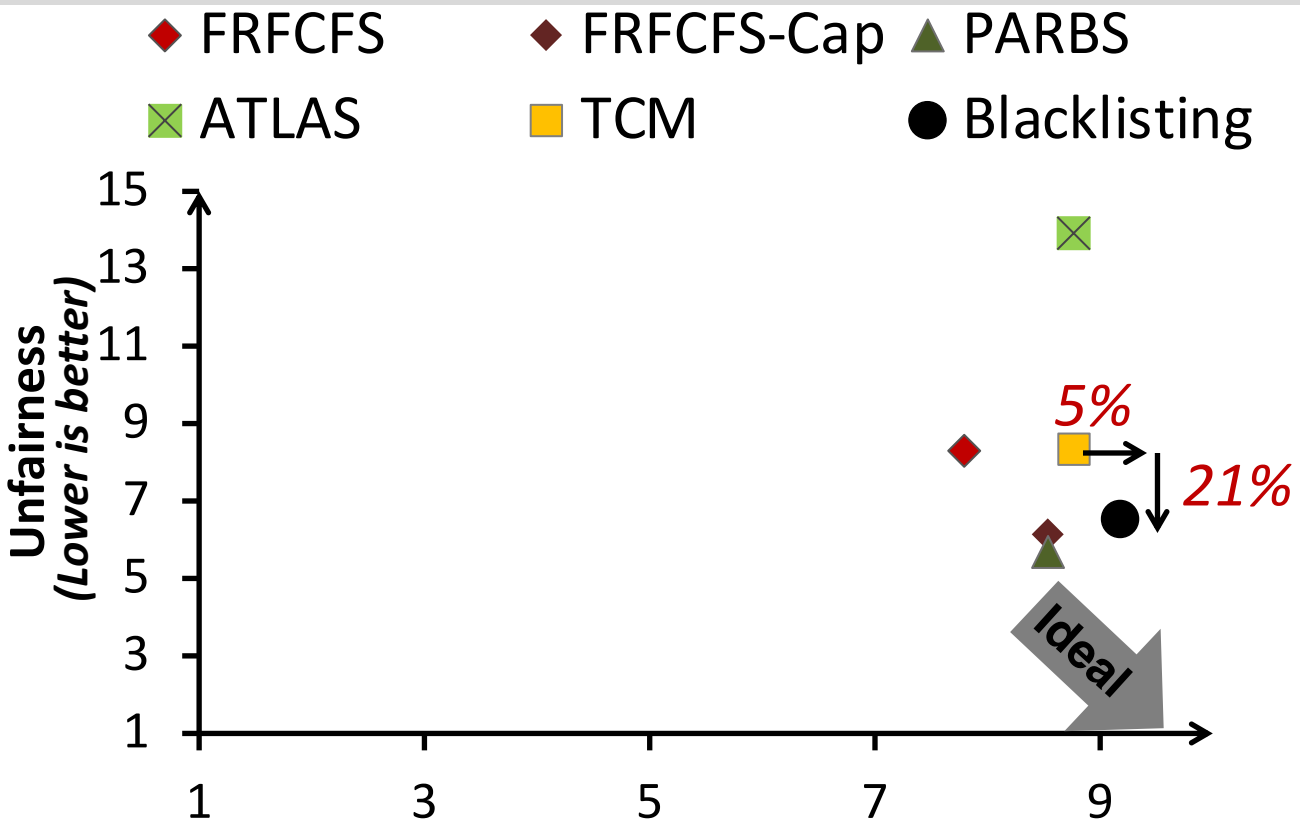
Benefits:

- *Lower complexity*
- *Finer grained grouping decisions* → *Lower unfairness*

Performance vs. Fairness vs. Simplicity



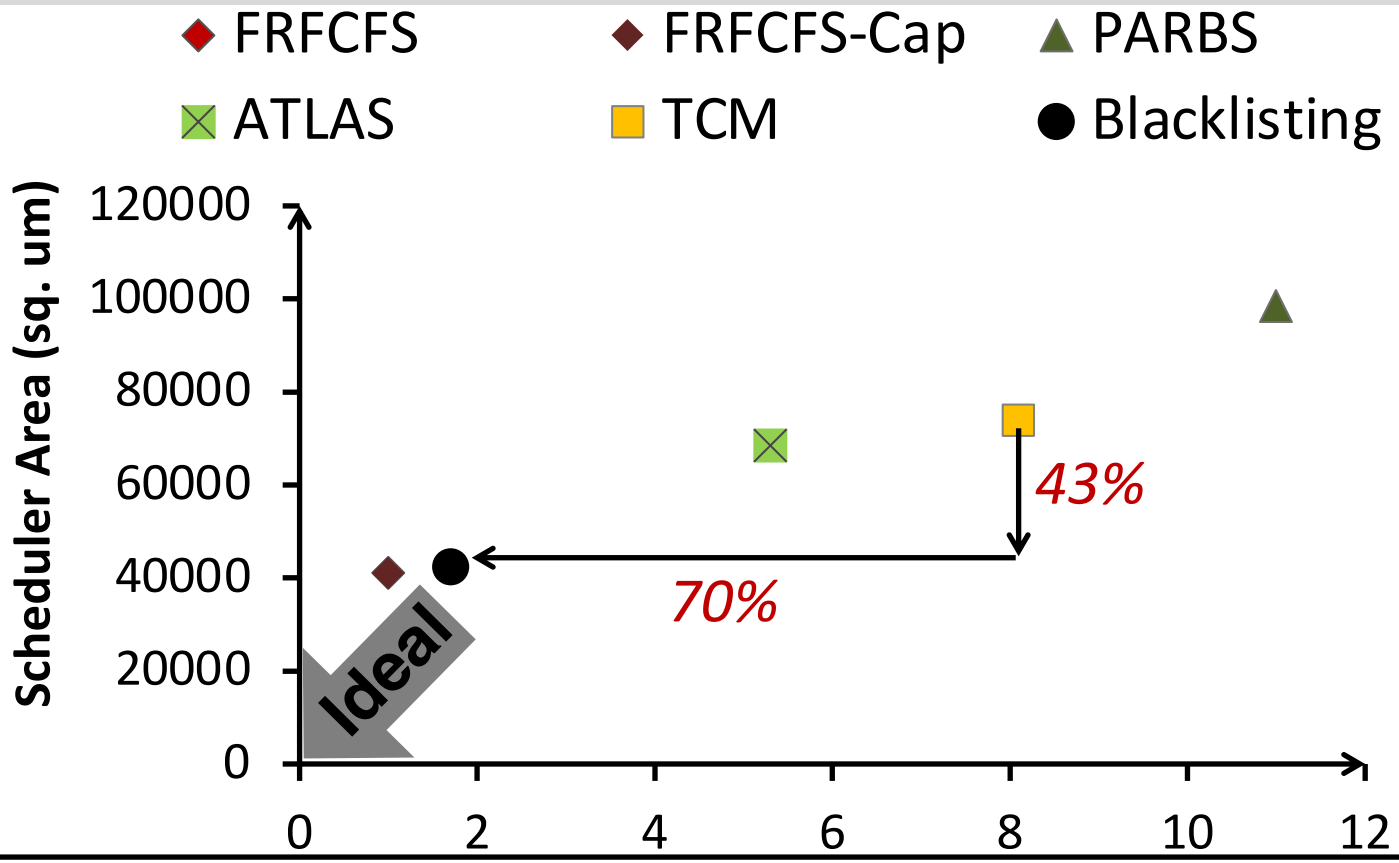
Performance and Fairness



1. Blacklisting achieves the highest performance

2. Blacklisting balances performance and fairness

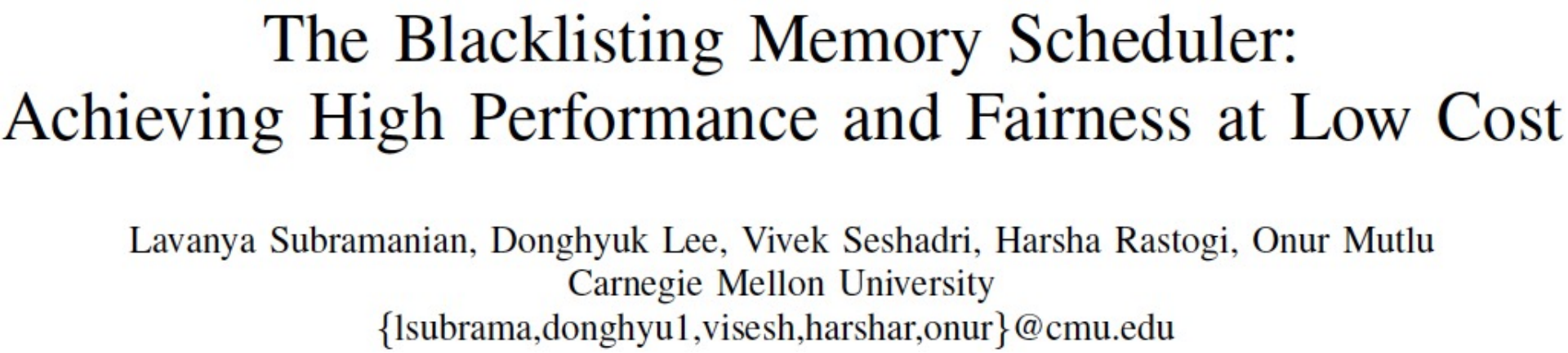
Complexity



Blacklisting reduces complexity significantly

More on BLISS (I)

- Lavanya Subramanian, Donghyuk Lee, Vivek Seshadri, Harsha Rastogi, and Onur Mutlu,
  "The Blacklisting Memory Scheduler: Achieving High Performance and Fairness at Low Cost"
  *Proceedings of the 32nd IEEE International Conference on Computer Design (**ICCD**)*, Seoul, South Korea, October 2014.
  [Slides (pptx) (pdf)]



The Blacklisting Memory Scheduler:
Achieving High Performance and Fairness at Low Cost

Lavanya Subramanian, Donghyuk Lee, Vivek Seshadri, Harsha Rastogi, Onur Mutlu
Carnegie Mellon University
{lsubrama,donghyu1,visesh,harshar,onur}@cmu.edu

More on BLISS: Longer Version

- Lavanya Subramanian, Donghyuk Lee, Vivek Seshadri, Harsha Rastogi, and Onur Mutlu,
  "BLISS: Balancing Performance, Fairness and Complexity in Memory Access Scheduling"
  IEEE Transactions on Parallel and Distributed Systems (***TPDS***), to appear in 2016. arXiv.org version, April 2015.
  An earlier version as *SAFARI Technical Report*, TR-SAFARI-2015-004, Carnegie Mellon University, March 2015.
  [Source Code]

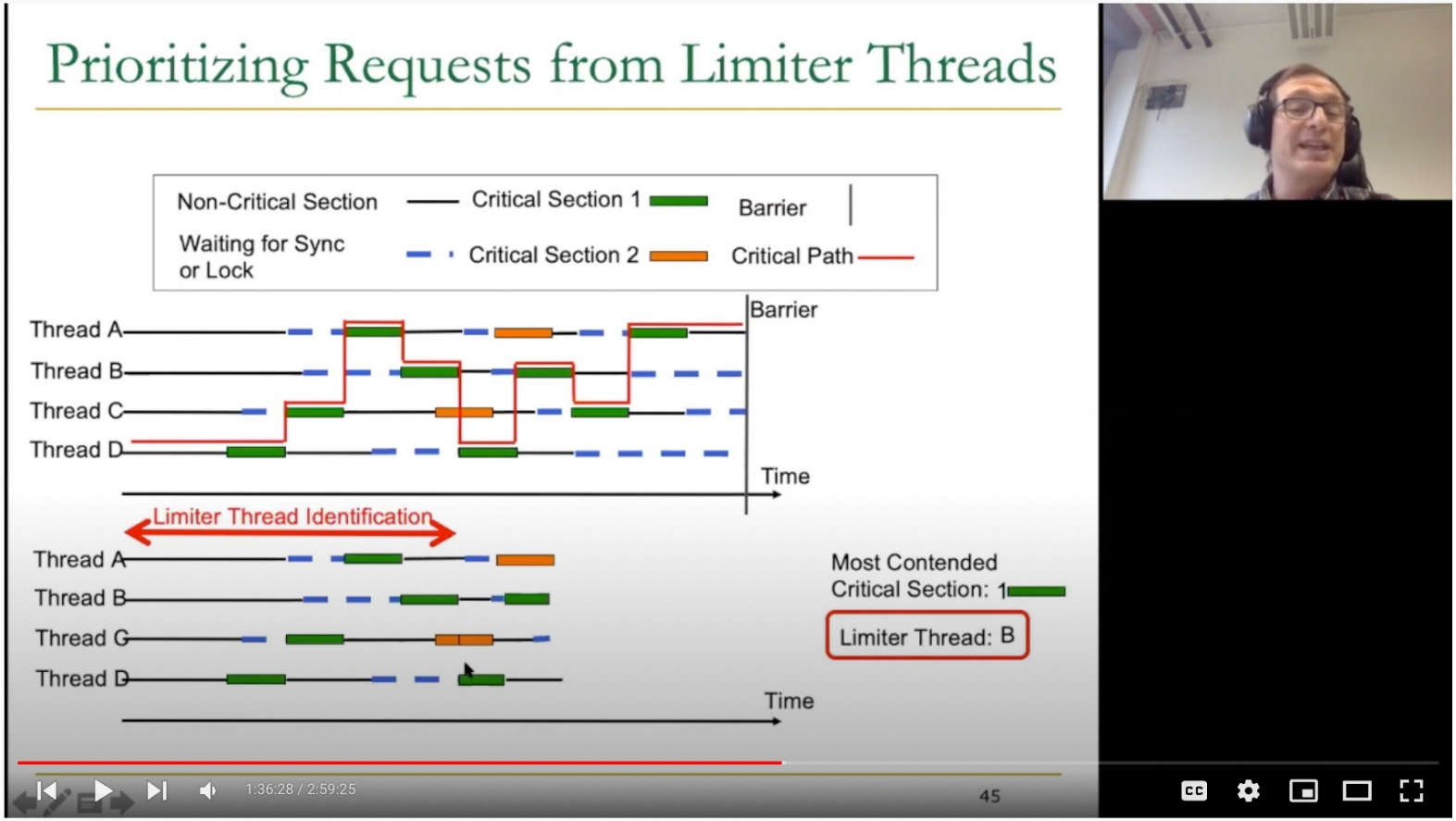
BLISS: Balancing Performance, Fairness and Complexity in Memory Access Scheduling

Lavanya Subramanian, Donghyuk Lee, Vivek Seshadri, Harsha Rastogi, and Onur Mutlu

Handling Memory Interference In Multithreaded Applications

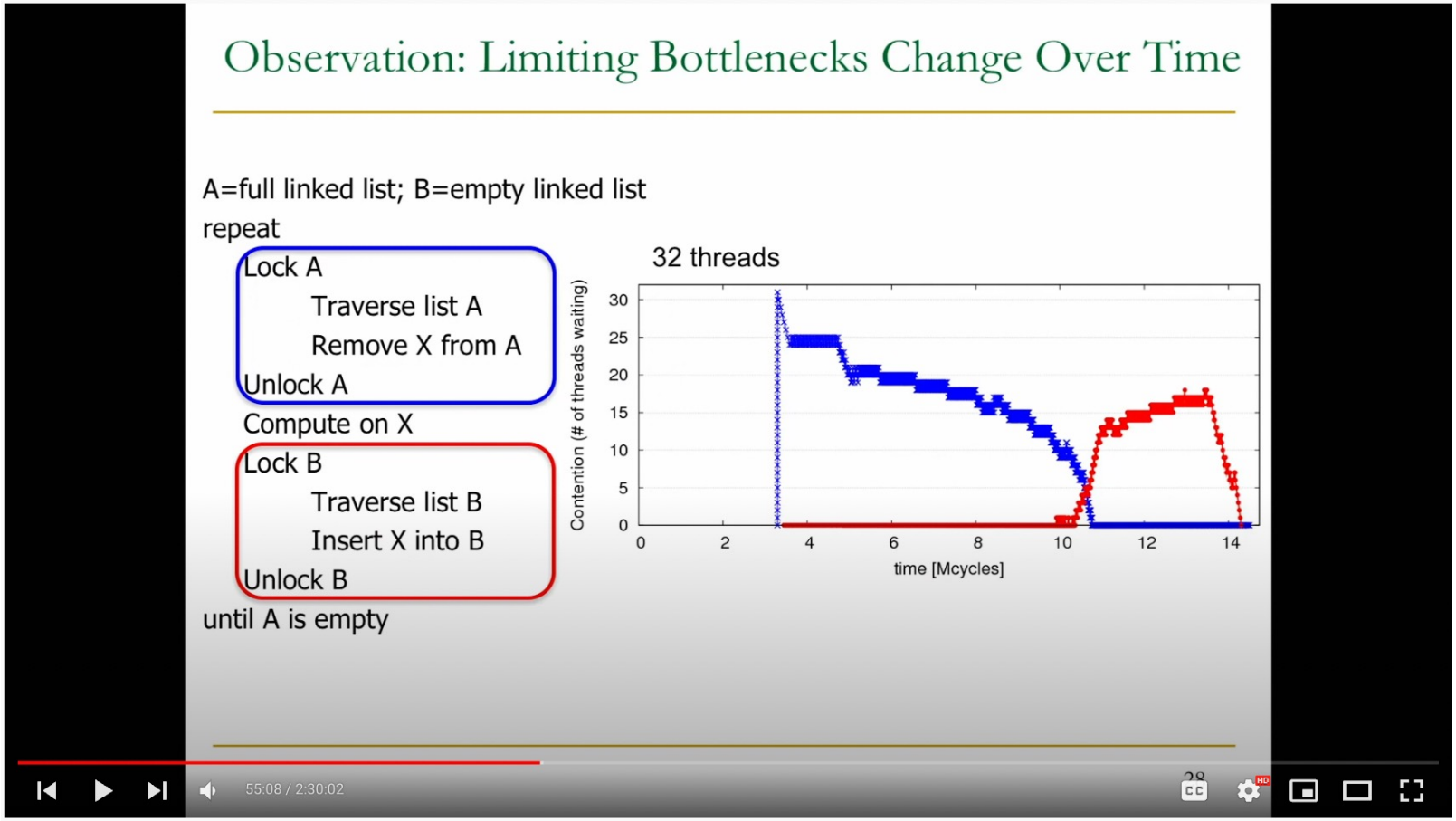
Eiman Ebrahimi, Rustam Miftakhutdinov, Chris Fallin,
Chang Joo Lee, Onur Mutlu, and Yale N. Patt,
"Parallel Application Memory Scheduling"
Proceedings of the 44th International Symposium on Microarchitecture (***MICRO***),
Porto Alegre, Brazil, December 2011. Slides (pptx)

Lecture on Parallel Application Scheduling



https://www.youtube.com/watch?v=Axye9VqQT7w&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=26

Lecture on Bottleneck Acceleration



https://www.youtube.com/watch?v=KQfKPcztsDQ&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=31

Multithreaded (Parallel) Applications

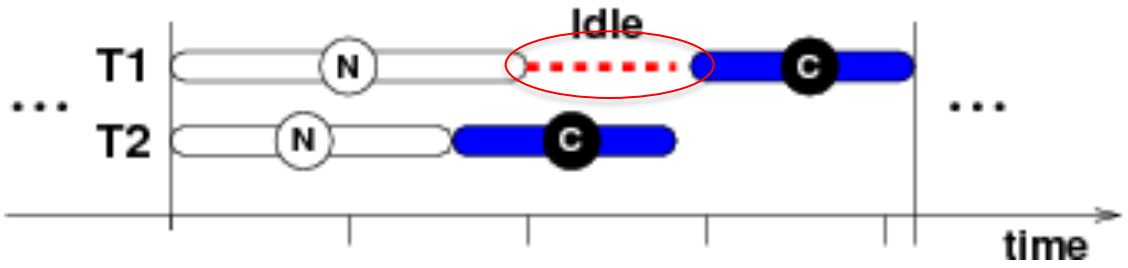
- Threads in a multi-threaded application can be inter-dependent
  - As opposed to threads from different applications
- Such threads can synchronize with each other
  - Locks, barriers, pipeline stages, condition variables, semaphores, …
- Some threads can be on the critical path of execution due to synchronization; some threads are not
- Even within a thread, some "code segments" may be on the critical path of execution; some are not

Critical Sections

- Enforce mutually exclusive access to shared data
- Only one thread can be executing it at a time
- Contended critical sections make threads wait → threads causing serialization can be on the critical path

Each thread:

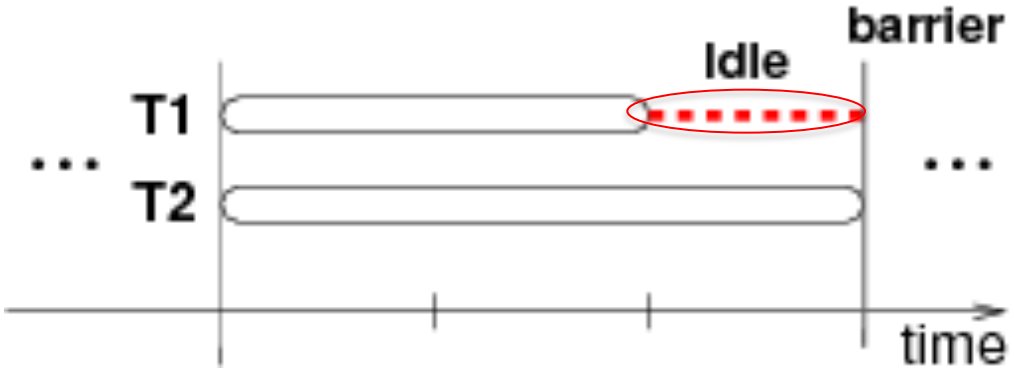
```
loop {
    Compute                    N
    lock(A)
        Update shared data
    unlock(A)                  C
}
```



Barriers

- Synchronization point
- Threads have to wait until all threads reach the barrier
- Last thread arriving at the barrier is on the critical path

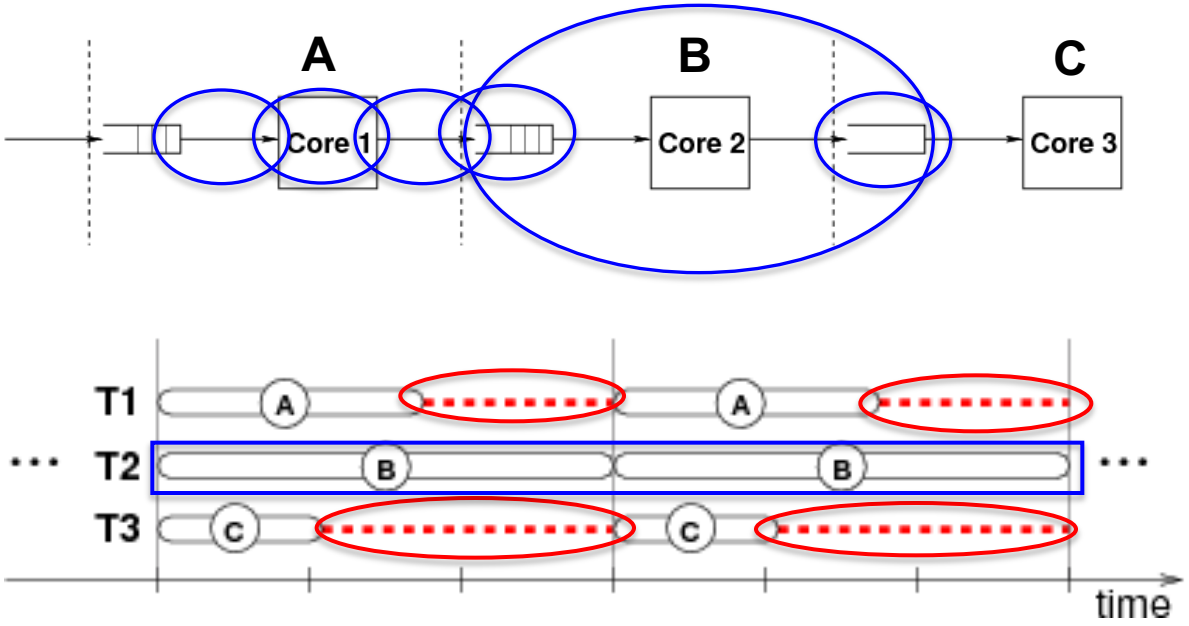
```
Each thread:
    loop1 {
        Compute
    }
    barrier
    loop2 {
        Compute
    }
```



Stages of Pipelined Programs

- Loop iterations are statically divided into code segments called *stages*
- Threads execute stages on different cores
- Thread executing the slowest stage is on the critical path

```
loop {
  Compute1   A
  Compute2   B
  Compute3   C
}
```



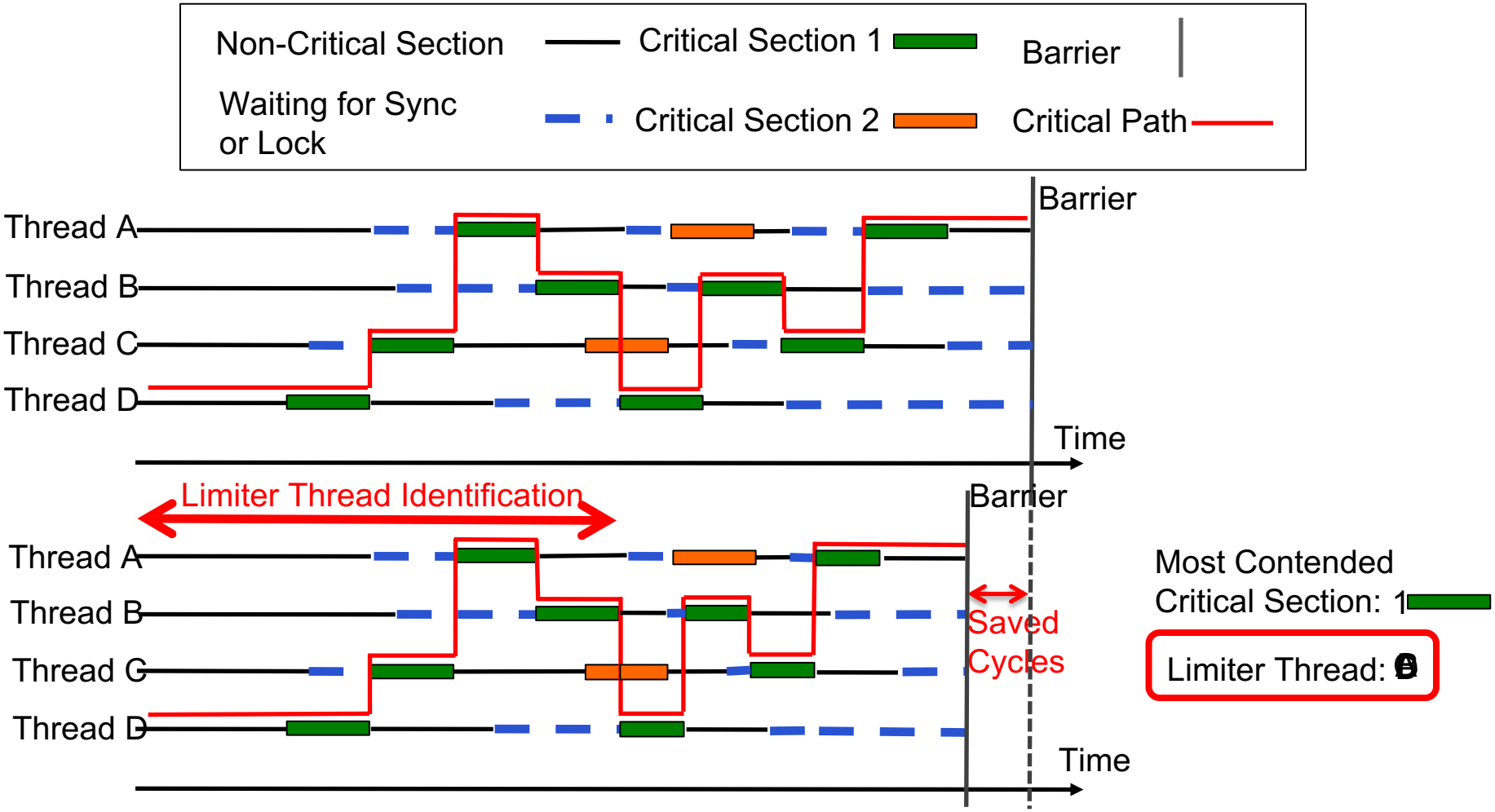
Handling Interference in Parallel Applications

- Threads in a multithreaded application are inter-dependent
- Some threads can be on the critical path of execution due to synchronization; some threads are not
- How do we schedule requests of inter-dependent threads to maximize multithreaded application performance?

- Idea: Estimate limiter threads likely to be on the critical path and prioritize their requests; shuffle priorities of non-limiter threads to reduce memory interference among them [Ebrahimi+, MICRO'11]

- Hardware/software cooperative limiter thread estimation:
  - Thread executing the most contended critical section
  - Thread executing the slowest pipeline stage
  - Thread that is falling behind the most in reaching a barrier

Prioritizing Requests from Limiter Threads



Parallel App Mem Scheduling: Pros and Cons

- Upsides:
  - Improves the performance of multi-threaded applications
  - Provides a mechanism for estimating "limiter threads"
  - Opens a path for slowdown estimation for multi-threaded applications

- Downsides:
  - What if there are multiple multi-threaded applications running together?
  - Limiter thread estimation can be complex
    - "Joao+, Bottleneck Identification and Scheduling, ASPLOS 2012"

More on PAMS

- Eiman Ebrahimi, Rustam Miftakhutdinov, Chris Fallin, Chang Joo Lee, Onur Mutlu, and Yale N. Patt, **"Parallel Application Memory Scheduling"** *Proceedings of the 44th International Symposium on Microarchitecture (**MICRO**)*, Porto Alegre, Brazil, December 2011. Slides (pptx)

Parallel Application Memory Scheduling

Eiman Ebrahimi† Rustam Miftakhutdinov† Chris Fallin§
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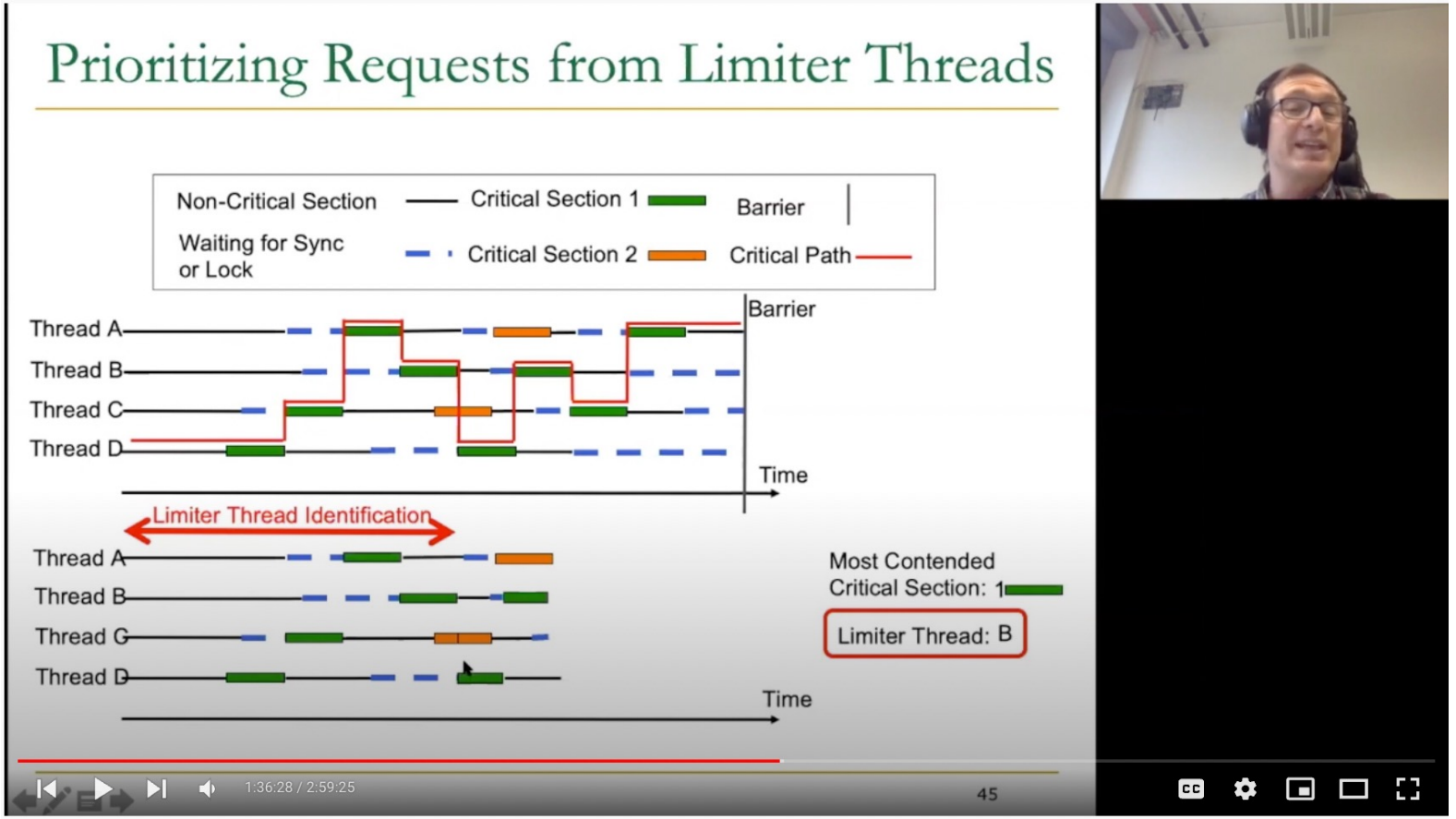
Lecture on Parallel Application Scheduling



https://www.youtube.com/watch?v=Axye9VqQT7w&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=26

Bottleneck Identification & Scheduling

- Jose A. Joao, M. Aater Suleman, Onur Mutlu, and Yale N. Patt, **"Bottleneck Identification and Scheduling in Multithreaded Applications"**
  *Proceedings of the 17th International Conference on Architectural Support for Programming Languages and Operating Systems (**ASPLOS**)*, London, UK, March 2012. Slides (ppt) (pdf)

Bottleneck Identification and Scheduling in Multithreaded Applications

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Carnegie Mellon University
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ECE Department
The University of Texas at Austin
patt@ece.utexas.edu

Utility-Based Bottleneck Acceleration

- Jose A. Joao, M. Aater Suleman, Onur Mutlu, and Yale N. Patt, **"Utility-Based Acceleration of Multithreaded Applications on Asymmetric CMPs"**
  *Proceedings of the 40th International Symposium on Computer Architecture (**ISCA**)*, Tel-Aviv, Israel, June 2013. Slides (ppt) Slides (pdf)

Utility-Based Acceleration of Multithreaded Applications on Asymmetric CMPs

José A. Joao † M. Aater Suleman ‡† Onur Mutlu § Yale N. Patt †

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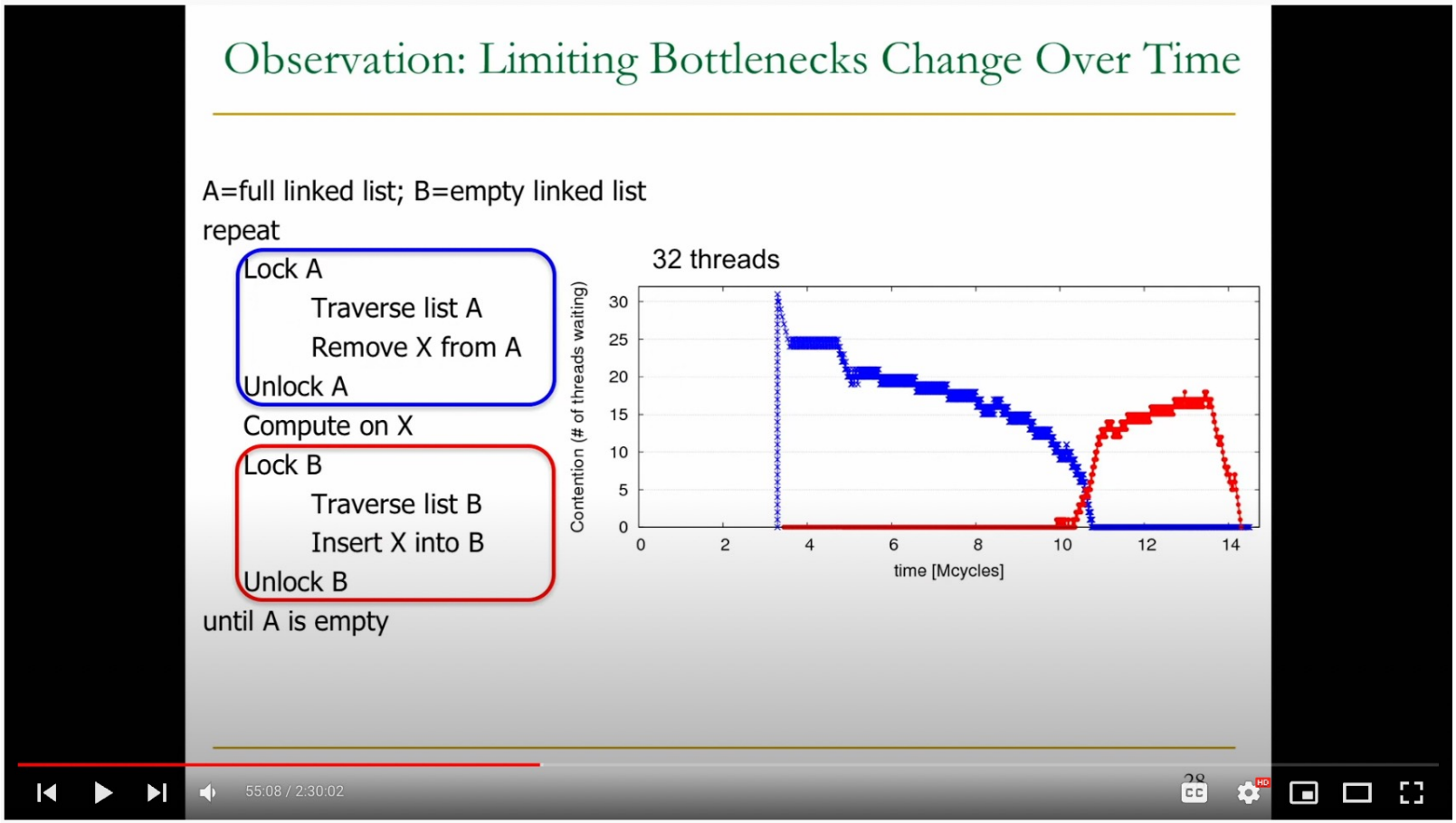
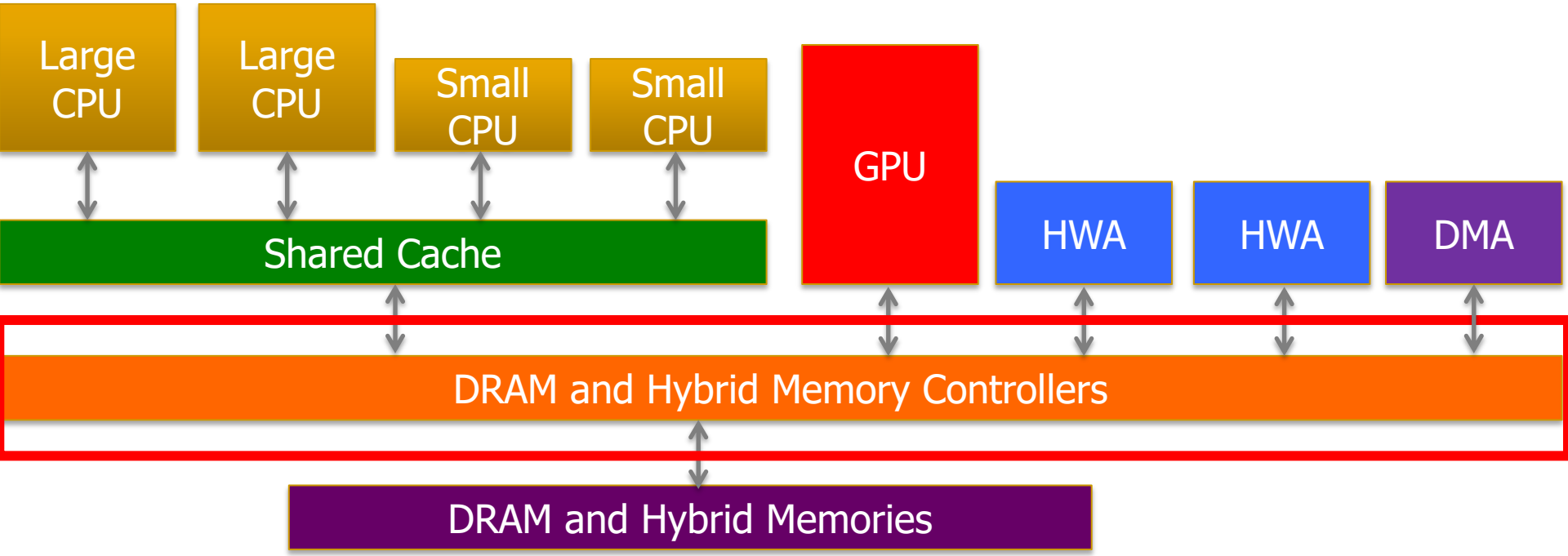
Lecture on Bottleneck Acceleration



https://www.youtube.com/watch?v=KQfKPcztsDQ&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=31

Memory Scheduling for Heterogeneous Systems

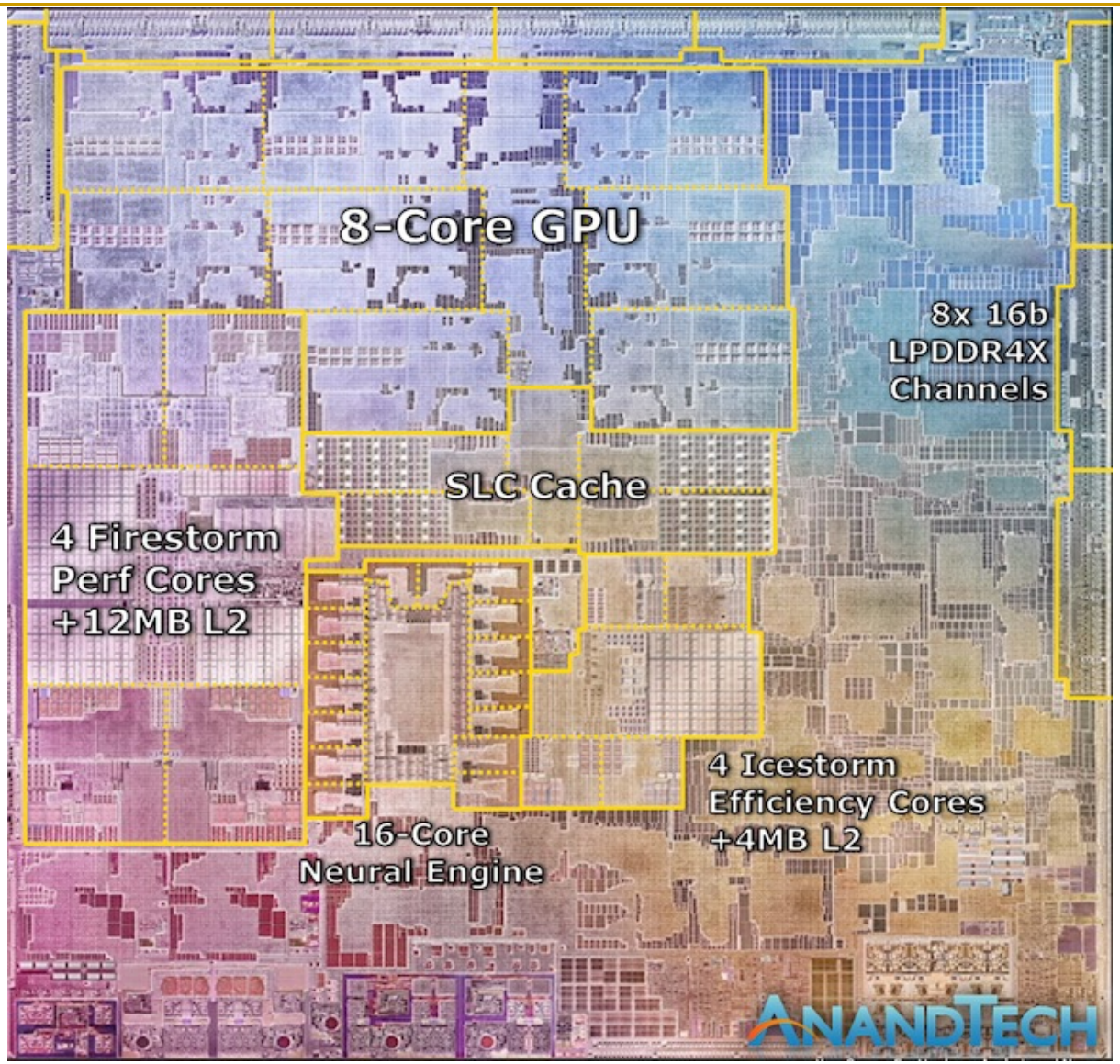
Current SoC Architectures: Heterogeneity



- Heterogeneous agents: CPUs, GPUs, HWAs, DMA engine, …
- Memory resources shared by CPUs/GPUs/HWAs → Interference

How to allocate resources to heterogeneous agents to mitigate interference and provide predictable performance?

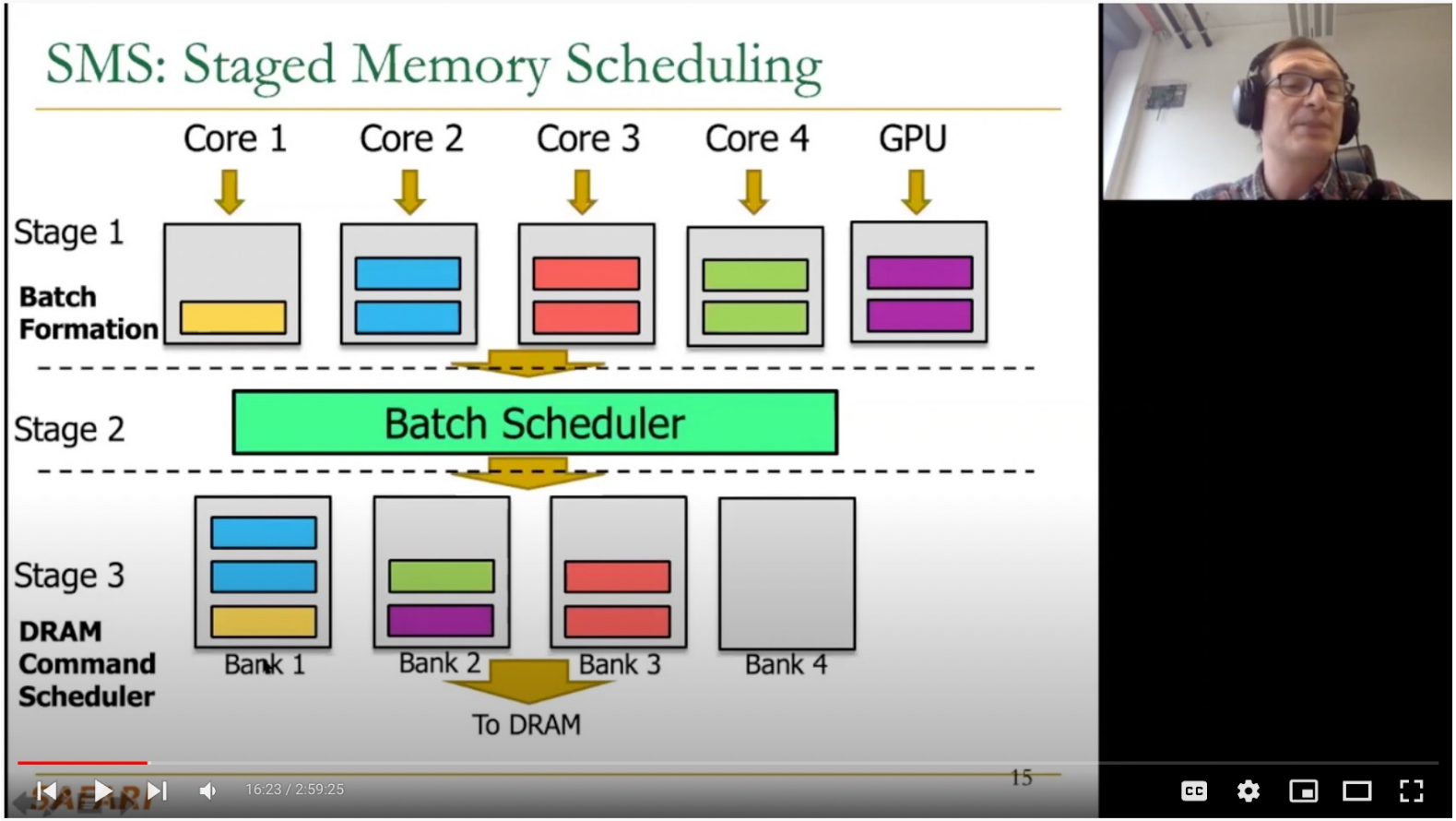
Current SoC Architectures: Heterogeneity



Apple M1, 2021

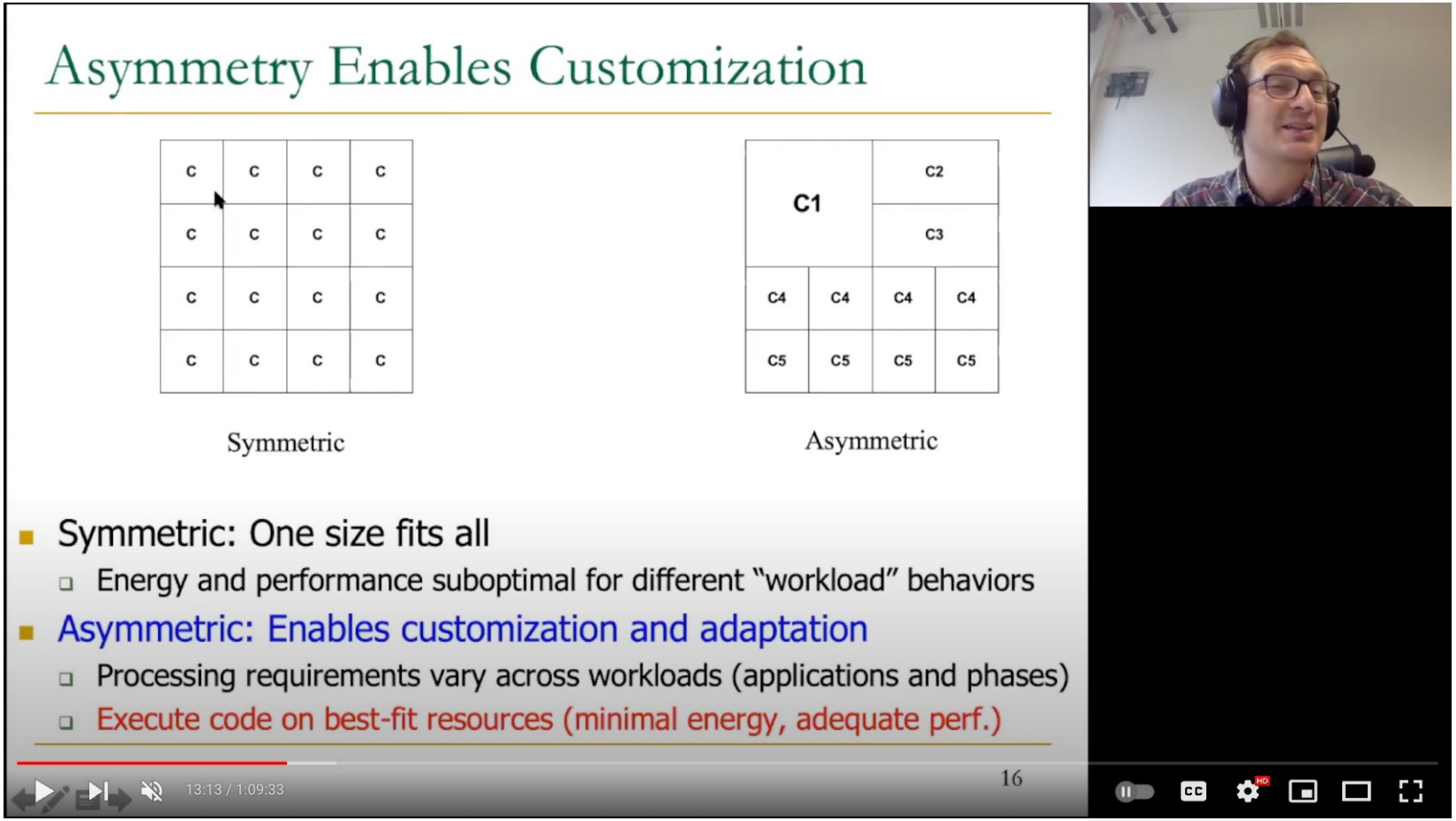
Source: https://www.anandtech.com/show/16252/mac-mini-apple-m1-tested

Lecture on Heterogeneous System Scheduling



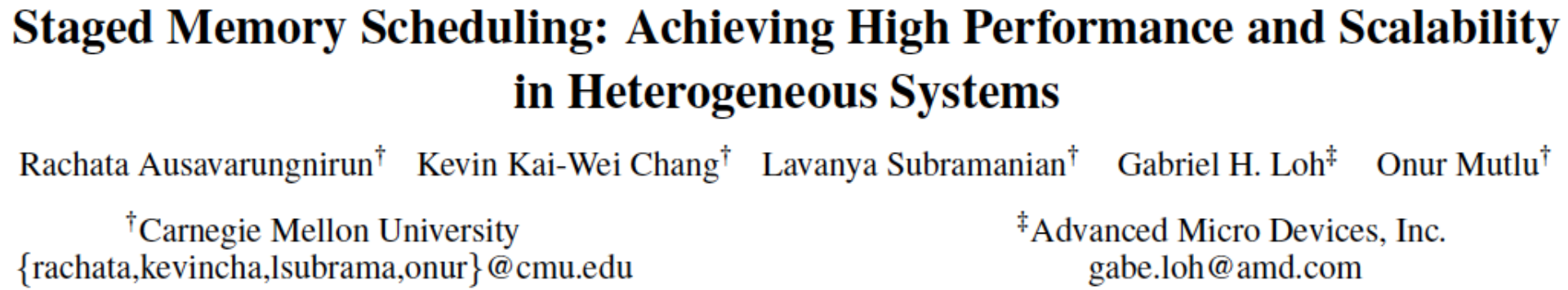
https://www.youtube.com/watch?v=Axye9VqQT7w&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=26

Lecture on Heterogeneous Computing Systems



Staged Memory Scheduling

- Rachata Ausavarungnirun, Kevin Chang, Lavanya Subramanian, Gabriel Loh, and Onur Mutlu,
  "Staged Memory Scheduling: Achieving High Performance and Scalability in Heterogeneous Systems"
  *Proceedings of the 39th International Symposium on Computer Architecture (**ISCA**)*, Portland, OR, June 2012. Slides (pptx)



Staged Memory Scheduling: Achieving High Performance and Scalability in Heterogeneous Systems

Rachata Ausavarungnirun[†] Kevin Kai-Wei Chang[†] Lavanya Subramanian[†] Gabriel H. Loh[‡] Onur Mutlu[†]

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{rachata,kevincha,lsubrama,onur}@cmu.edu

[‡]Advanced Micro Devices, Inc.
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DASH: Deadline-Aware Memory Scheduler

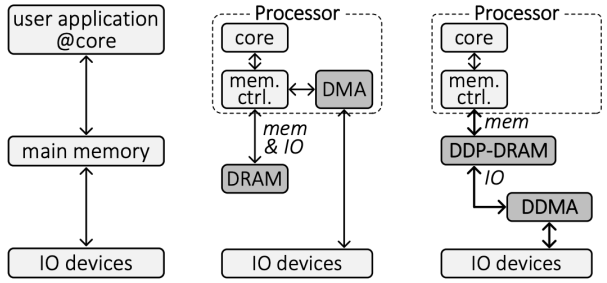
- Hiroyuki Usui, Lavanya Subramanian, Kevin Kai-Wei Chang, and Onur Mutlu,
  "DASH: Deadline-Aware High-Performance Memory Scheduler for Heterogeneous Systems with Hardware Accelerators"
  ACM Transactions on Architecture and Code Optimization (***TACO***),
  Vol. 12, January 2016.
  Presented at the 11th HiPEAC Conference, Prague, Czech Republic, January 2016.
  [Slides (pptx) (pdf)]
  [Source Code]

DASH: Deadline-Aware High-Performance Memory Scheduler for Heterogeneous Systems with Hardware Accelerators

HIROYUKI USUI, LAVANYA SUBRAMANIAN, KEVIN KAI-WEI CHANG, and ONUR MUTLU, Carnegie Mellon University

Handling CPU-IO Interference

Donghyuk Lee, Lavanya Subramanian, Rachata Ausavarungnirun, Jongmoo Choi, and Onur Mutlu,
"Decoupled Direct Memory Access: Isolating CPU and IO Traffic by Leveraging a Dual-Data-Port DRAM"
*Proceedings of the 24th International Conference on Parallel Architectures and Compilation Techniques (**PACT**)*, San Francisco, CA, USA, October 2015.
[Slides (pptx) (pdf)]



(a) Logical Hierarchy (b) Physical System (c) Our Proposal

Figure 1: Methods to Connect Cores and Data Sources

Decoupled Direct Memory Access:
Isolating CPU and IO Traffic by Leveraging a Dual-Data-Port DRAM

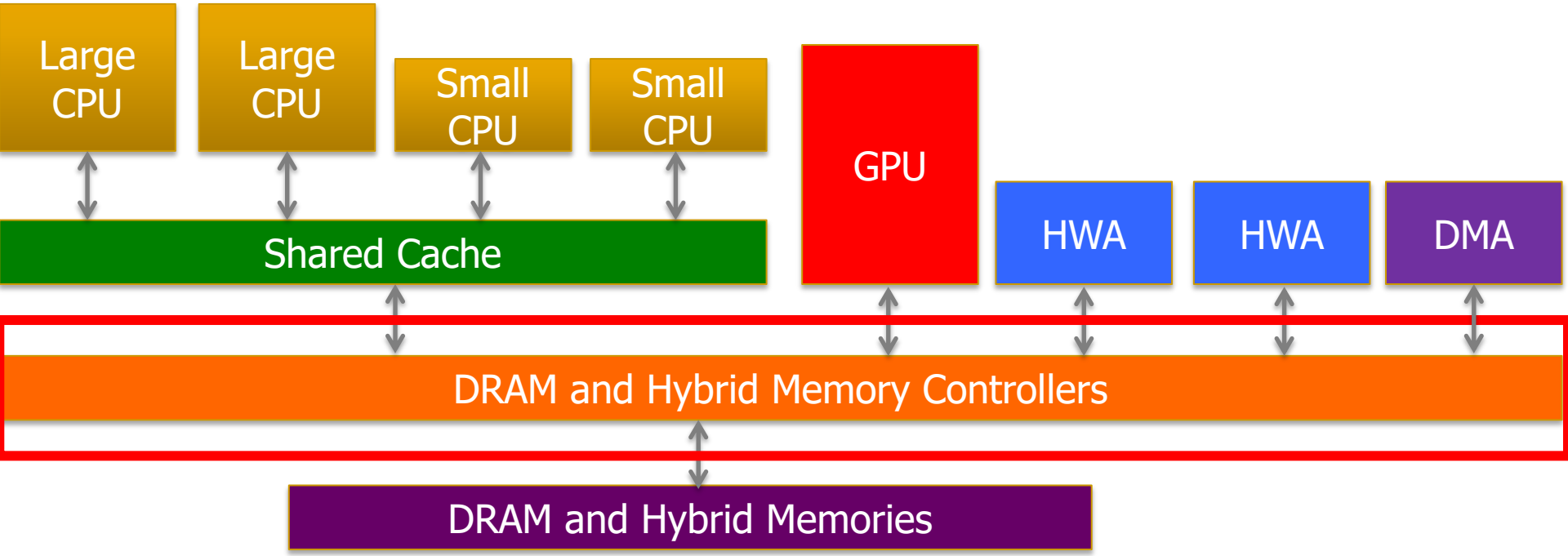
Donghyuk Lee* Lavanya Subramanian* Rachata Ausavarungnirun* Jongmoo Choi† Onur Mutlu*

*Carnegie Mellon University †Dankook University

{donghyu1, lsubrama, rachata, onur}@cmu.edu choijm@dankook.ac.kr

Predictable Performance: Strong Memory Service Guarantees

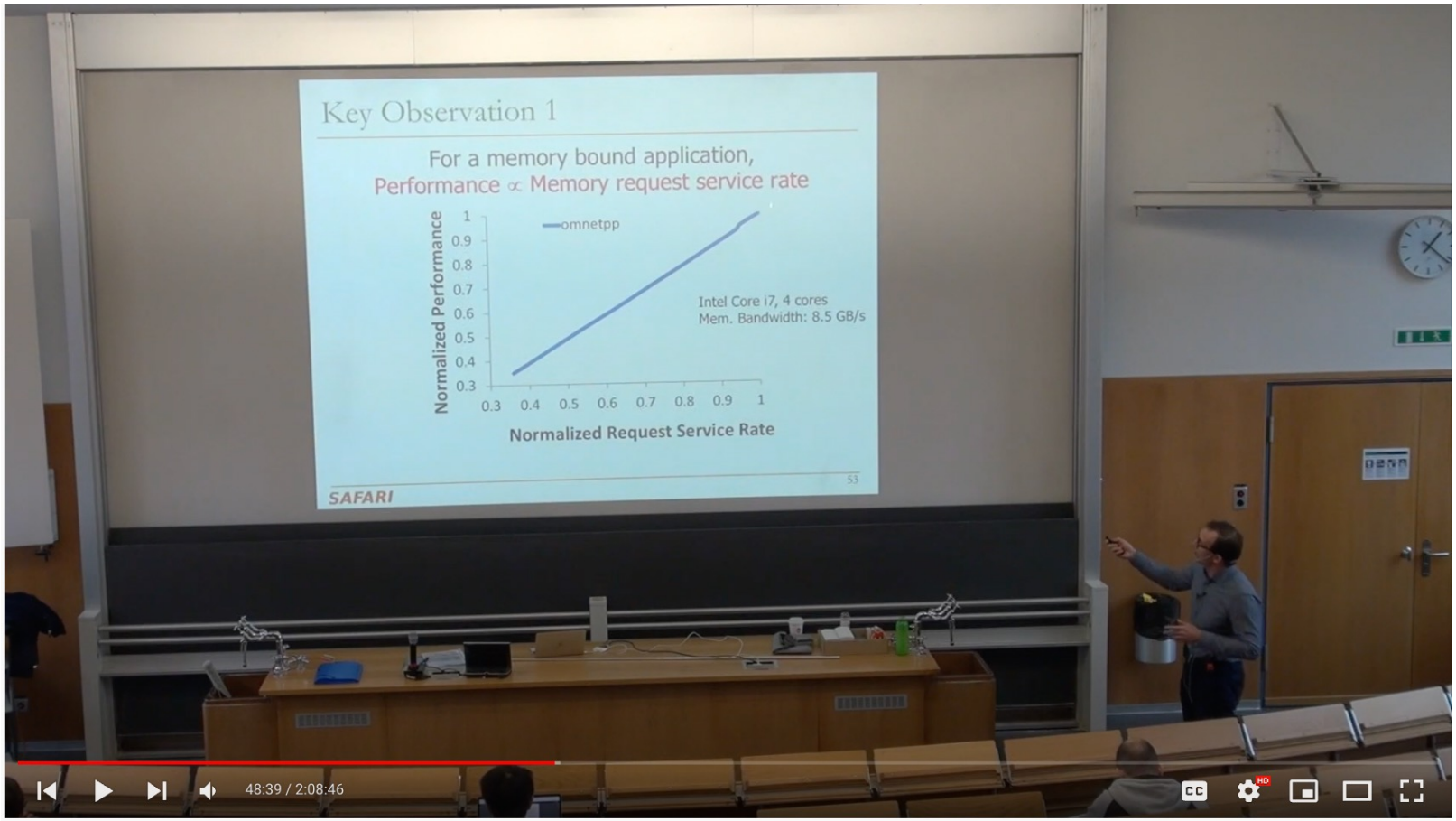
Goal: Predictable Performance in Complex Systems



- Heterogeneous agents: CPUs, GPUs, HWAs, DMA engine, …
- Memory resources shared by CPUs/GPUs/HWAs → Interference

How to allocate resources to heterogeneous agents to mitigate interference and provide predictable performance?

Lecture on Predictable Performance



ETH ZÜRICH HAUPTGEBÄUDE

Computer Architecture - Lecture 17: Memory Interference and QoS II (ETH Zürich, Fall 2018)

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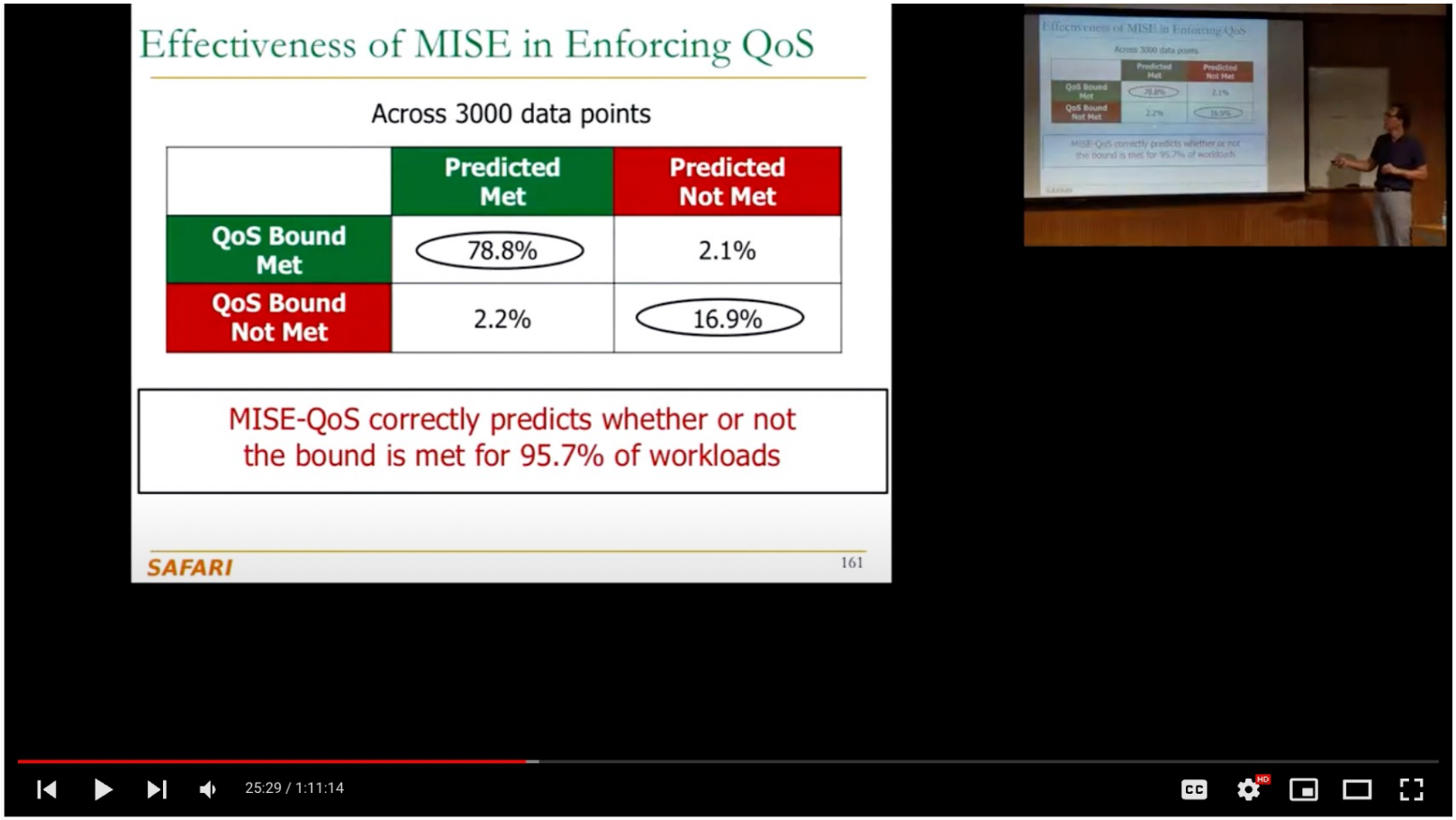
Lecture on Predictable Performance



https://www.youtube.com/watch?v=15hRJLhGWGA&list=PL5Q2soXY2Zi-IymxXpH_9vlZCOeA7Yfn9&index=19

Predictable Performance Readings (I)

Eiman Ebrahimi, Chang Joo Lee, Onur Mutlu, and Yale N. Patt,
"Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems"
*Proceedings of the 15th International Conference on Architectural Support for Programming Languages and Operating Systems (**ASPLOS**)*, pages 335-346, Pittsburgh, PA, March 2010. Slides (pdf)
Best paper award.

Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems

Eiman Ebrahimi† Chang Joo Lee† Onur Mutlu§ Yale N. Patt†

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{ebrahimi, cjlee, patt}@ece.utexas.edu

§Computer Architecture Laboratory (CALCM)
Carnegie Mellon University
onur@cmu.edu

Predictable Performance Readings (II)

- Lavanya Subramanian, Vivek Seshadri, Yoongu Kim, Ben Jaiyen, and Onur Mutlu,
  "MISE: Providing Performance Predictability and Improving Fairness in Shared Main Memory Systems"
  *Proceedings of the 19th International Symposium on High-Performance Computer Architecture (**HPCA**)*, Shenzhen, China, February 2013. Slides (pptx)

MISE: Providing Performance Predictability and Improving Fairness in Shared Main Memory Systems

Lavanya Subramanian Vivek Seshadri Yoongu Kim Ben Jaiyen Onur Mutlu

Carnegie Mellon University

Predictable Performance Readings (III)

- Lavanya Subramanian, Vivek Seshadri, Arnab Ghosh, Samira Khan, and Onur Mutlu,
  "The Application Slowdown Model: Quantifying and Controlling the Impact of Inter-Application Interference at Shared Caches and Main Memory"
  *Proceedings of the 48th International Symposium on Microarchitecture (**MICRO**)*, Waikiki, Hawaii, USA, December 2015.
  [Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)] [Poster (pptx) (pdf)]
  [Source Code]

The Application Slowdown Model: Quantifying and Controlling the Impact of Inter-Application Interference at Shared Caches and Main Memory

Lavanya Subramanian*§ Vivek Seshadri* Arnab Ghosh*†
Samira Khan*‡ Onur Mutlu*

*Carnegie Mellon University §Intel Labs †IIT Kanpur ‡University of Virginia

Predictable Performance Readings (IV)

- Hiroyuki Usui, Lavanya Subramanian, Kevin Kai-Wei Chang, and Onur Mutlu,
  "DASH: Deadline-Aware High-Performance Memory Scheduler for Heterogeneous Systems with Hardware Accelerators"
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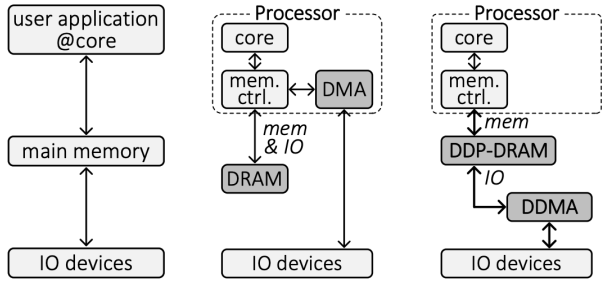

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Other QoS Approaches

Recall: Fundamental Interference Control Techniques

- Goal: to reduce/control inter-thread memory interference

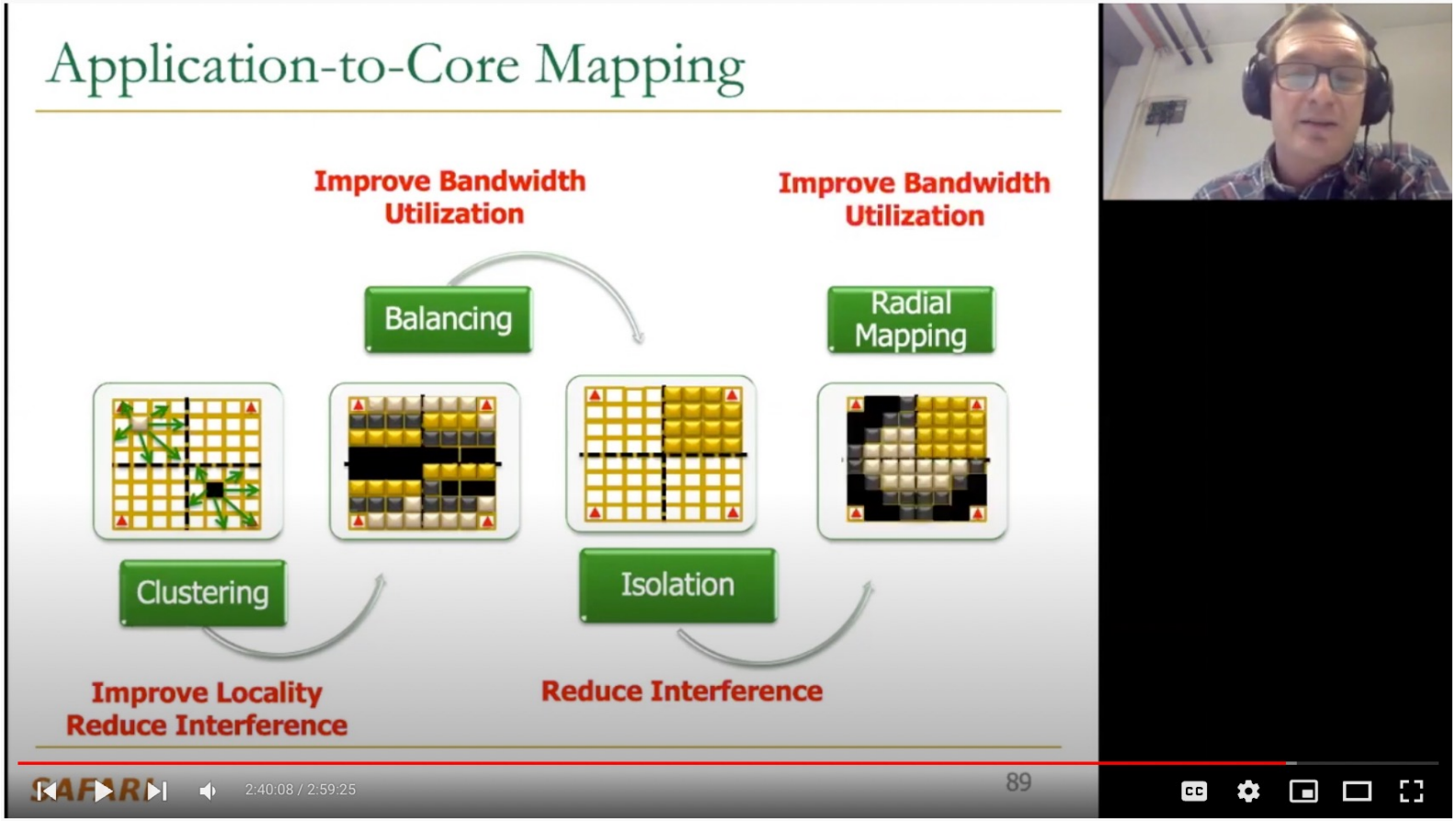
1. Prioritization or request scheduling

2. Data mapping to banks/channels/ranks

3. Core/source throttling

4. Application/thread scheduling

Lecture on Other QoS Techniques



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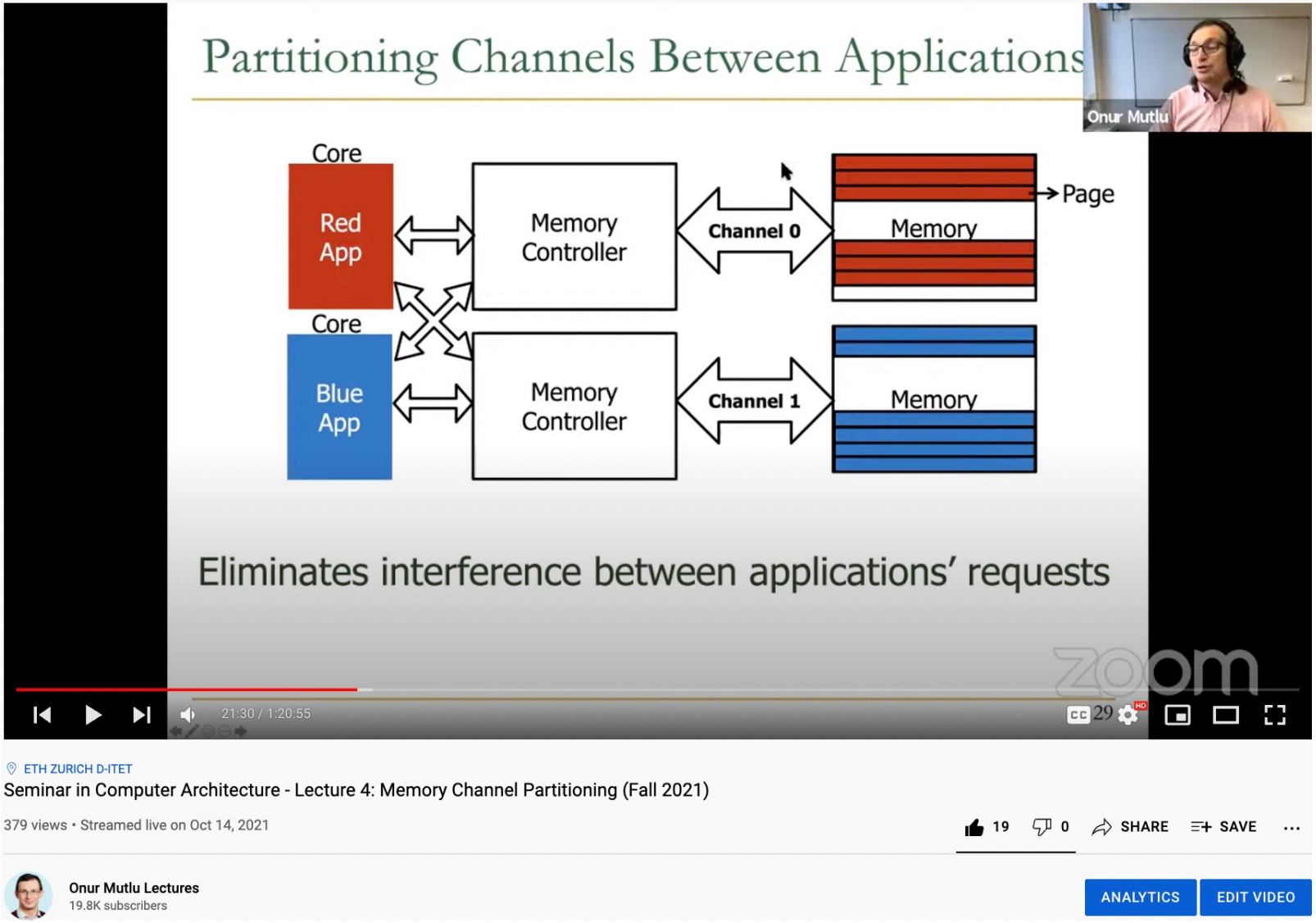
Memory Channel Partitioning



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Memory Channel Partitioning

- Sai Prashanth Muralidhara, Lavanya Subramanian, Onur Mutlu, Mahmut Kandemir, and Thomas Moscibroda, **"Reducing Memory Interference in Multicore Systems via Application-Aware Memory Channel Partitioning"** *Proceedings of the 44th International Symposium on Microarchitecture (**MICRO**)*, Porto Alegre, Brazil, December 2011. Slides (pptx)

Reducing Memory Interference in Multicore Systems via Application-Aware Memory Channel Partitioning

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https://www.youtube.com/watch?v=yEYEzFwAY9g

Memory Channel Partitioning

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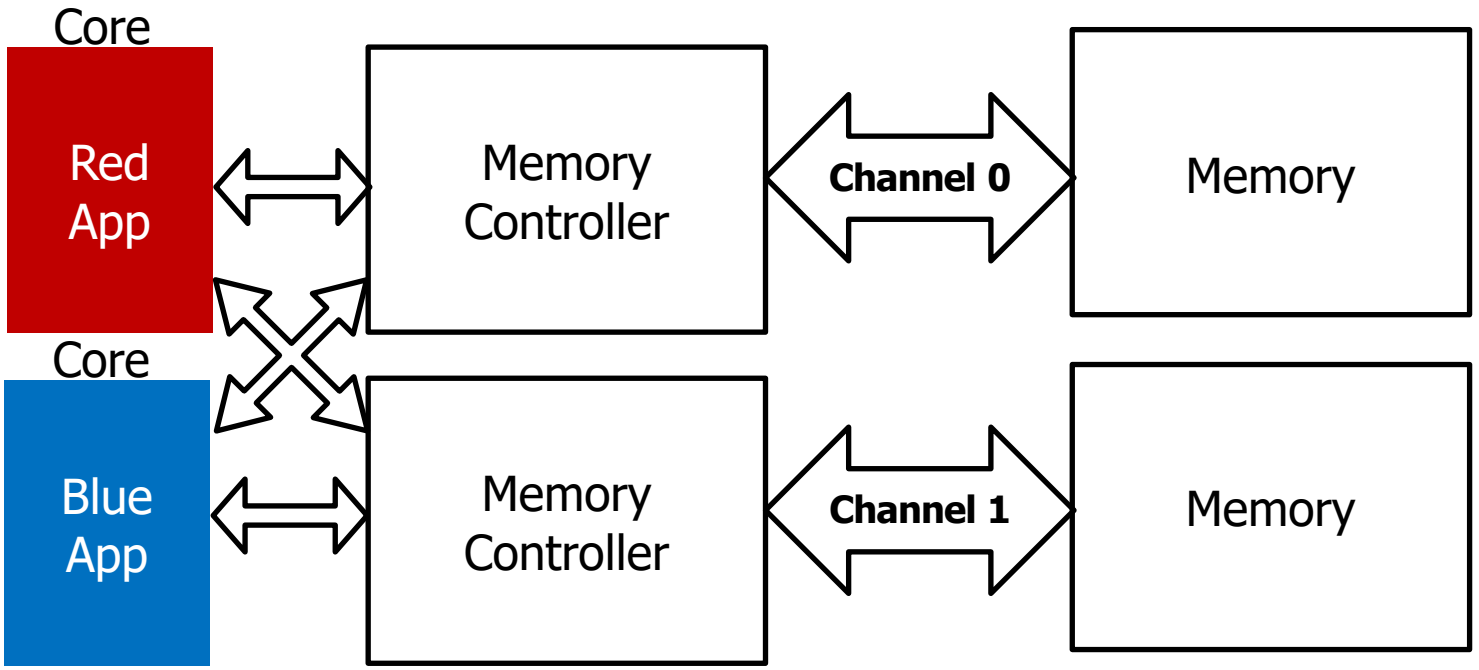
"Reducing Memory Interference in Multicore Systems via Application-Aware Memory Channel Partitioning"
44th International Symposium on Microarchitecture (***MICRO***),
Porto Alegre, Brazil, December 2011. Slides (pptx)

MCP Micro 2011 Talk

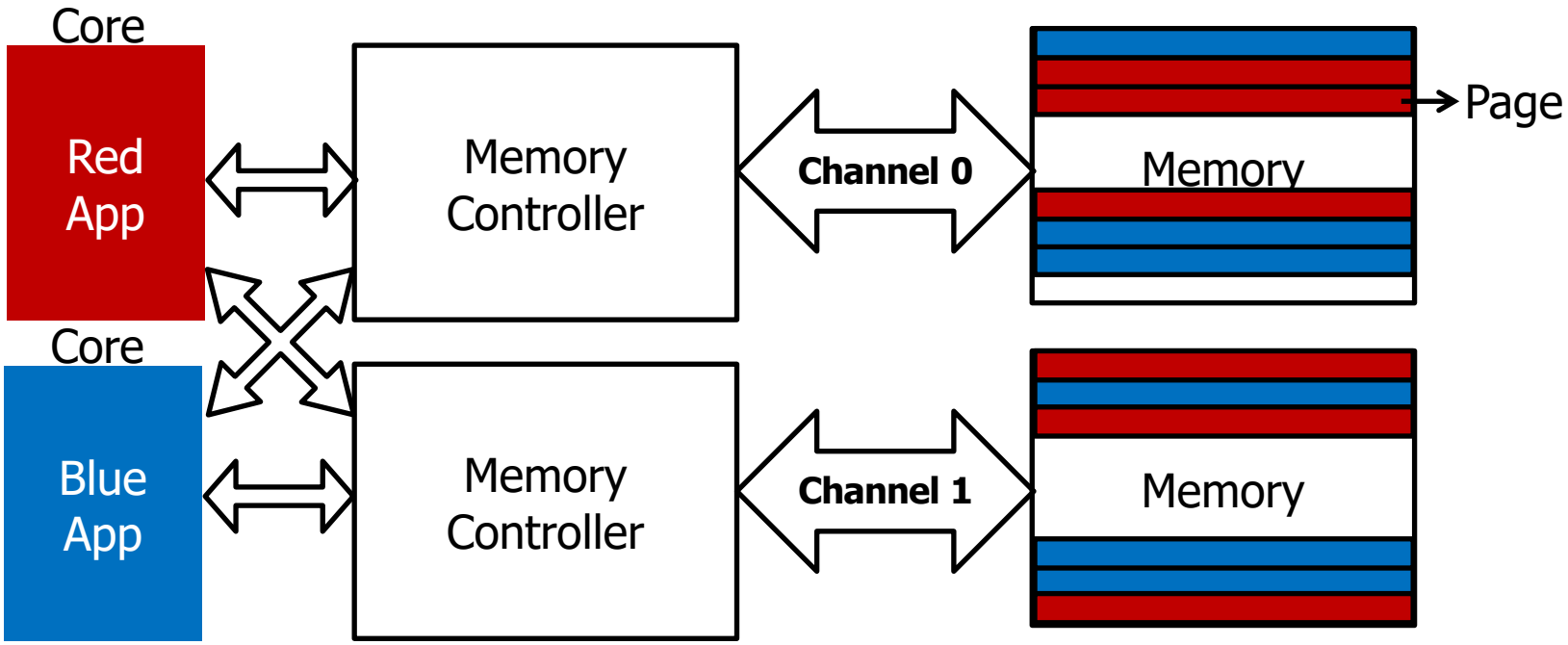
Observation: Modern Systems Have Multiple Channels



A new degree of freedom

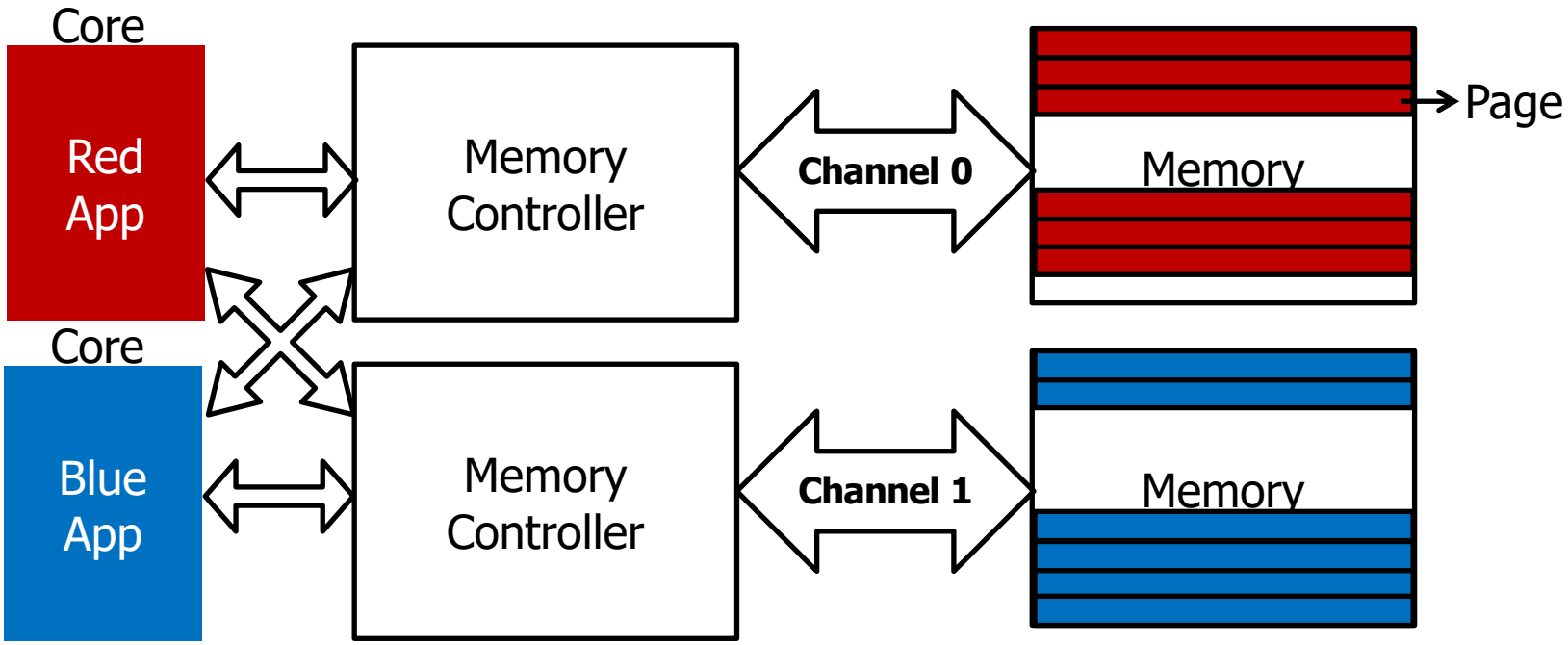
Mapping data across multiple channels

Data Mapping in Current Systems



Causes interference between applications' requests

Partitioning Channels Between Applications



Eliminates interference between applications' requests

Overview: Memory Channel Partitioning (MCP)

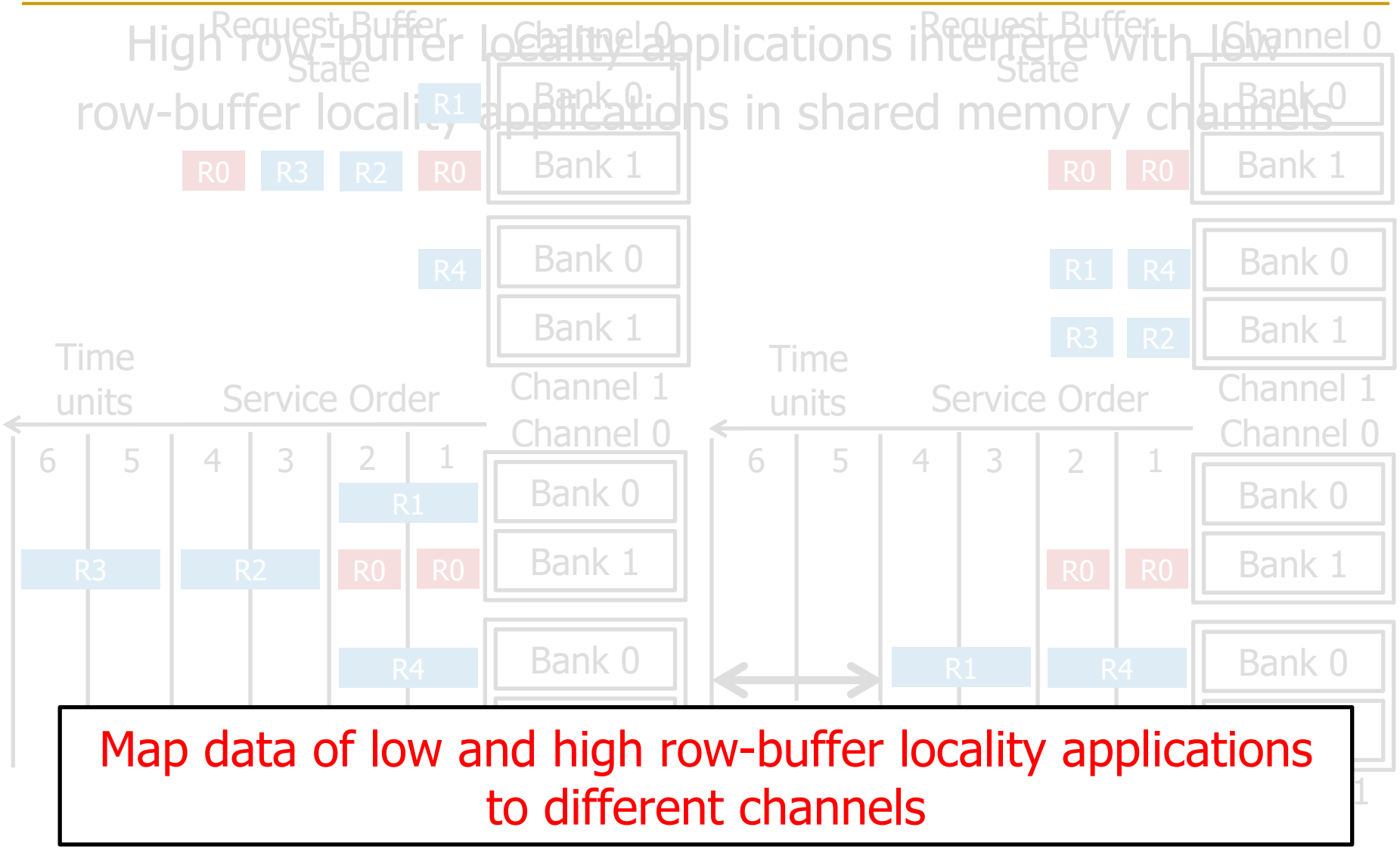
- Goal
  - Eliminate harmful interference between applications
- Basic Idea
  - Map the data of badly-interfering applications to different channels
- Key Principles
  - Separate low and high memory-intensity applications
  - Separate low and high row-buffer locality applications

Key Insight 1: Separate by Memory Intensity

High memory-intensity applications interfere with low memory-intensity applications in shared memory channels

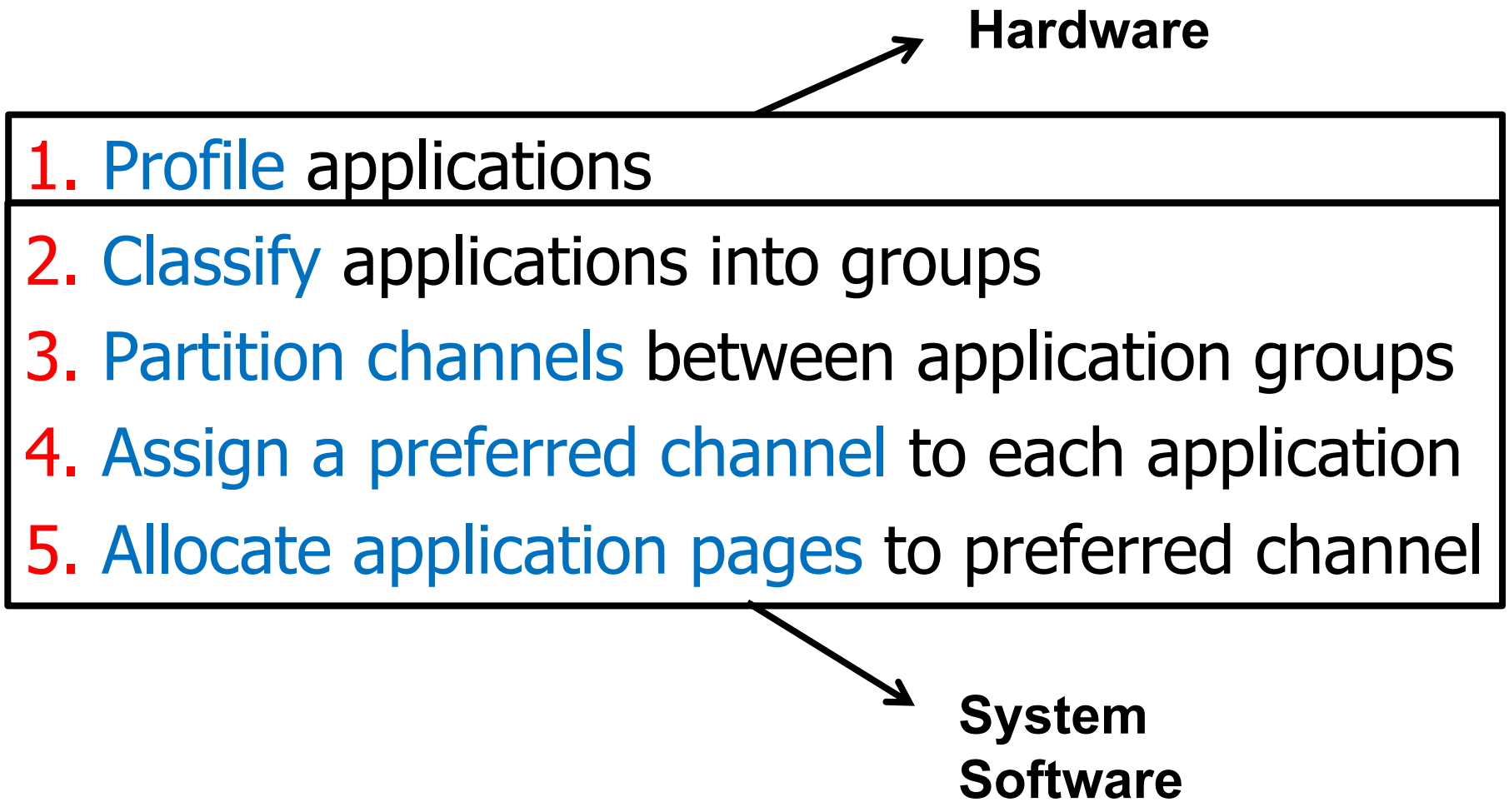
Map data of low and high memory-intensity applications to different channels

Key Insight 2: Separate by Row-Buffer Locality



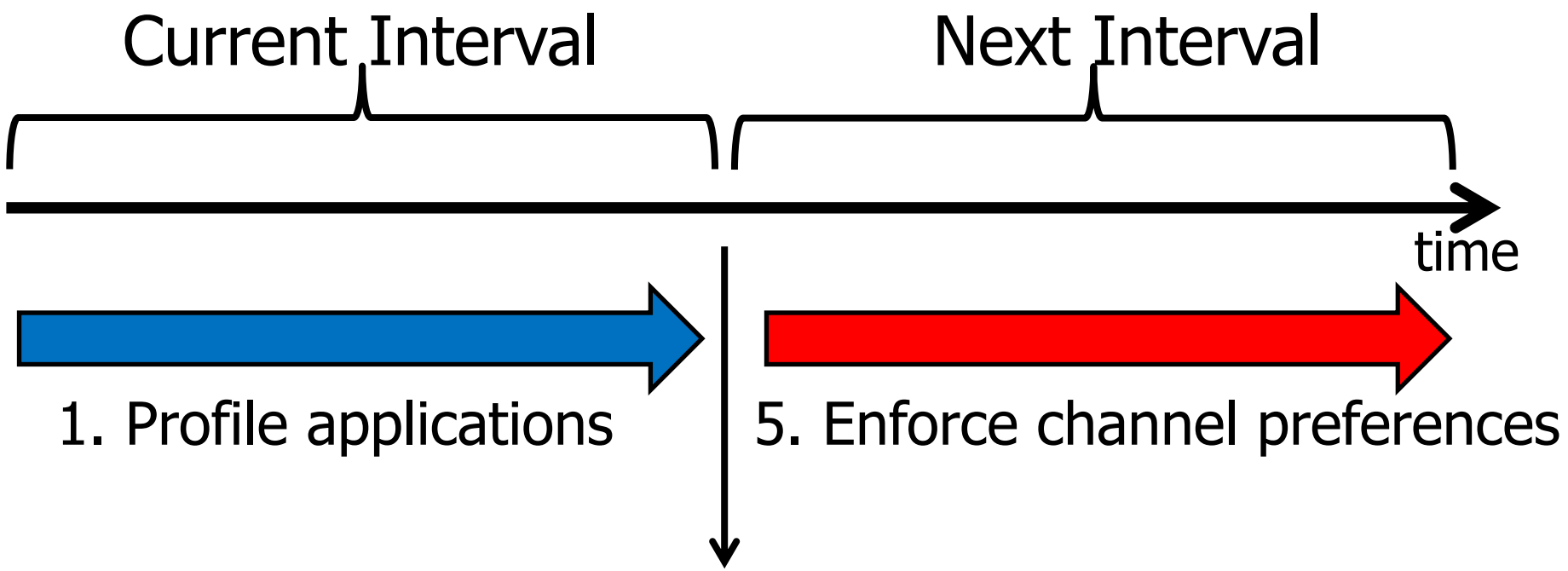
Map data of low and high row-buffer locality applications to different channels

Memory Channel Partitioning (MCP) Mechanism



Muralidhara et al., "Memory Channel Partitioning," MICRO'11.

Interval Based Operation



2. Classify applications into groups
3. Partition channels between groups
4. Assign preferred channel to applications

Observations

- Applications with very low memory-intensity rarely access memory
  → Dedicating channels to them results in precious memory bandwidth waste
- They have the most potential to keep their cores busy
  → We would really like to prioritize them
- They interfere minimally with other applications
  → Prioritizing them does not hurt others

Integrated Memory Partitioning and Scheduling (IMPS)

- Always prioritize very low memory-intensity applications in the memory scheduler

- Use memory channel partitioning to mitigate interference between other applications

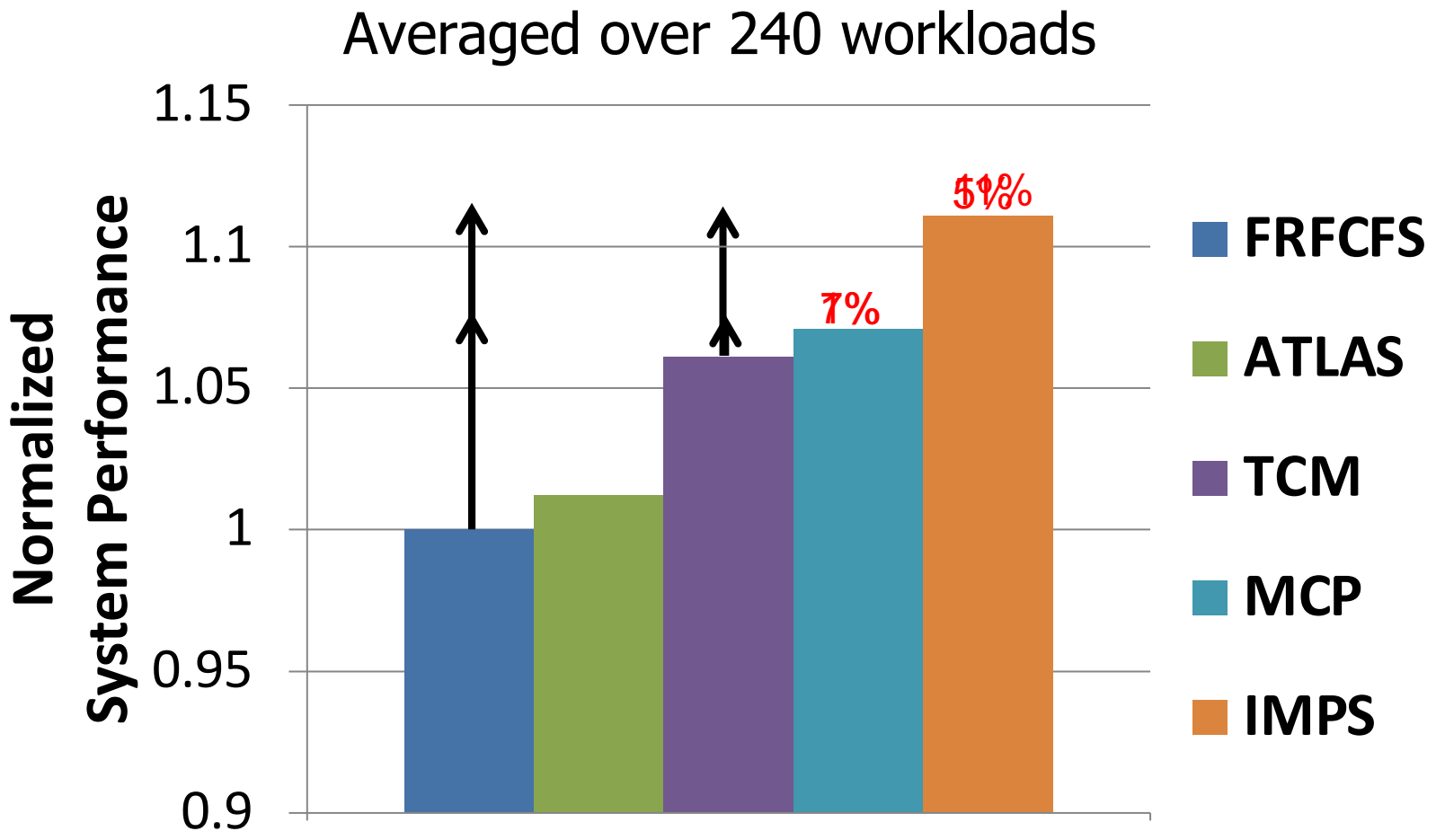
Muralidhara et al., "Memory Channel Partitioning," MICRO'11.

Hardware Cost

- Memory Channel Partitioning (MCP)
  - Only profiling counters in hardware
  - No modifications to memory scheduling logic
  - 1.5 KB storage cost for a 24-core, 4-channel system

- Integrated Memory Partitioning and Scheduling (IMPS)
  - A single bit per request
  - Scheduler prioritizes based on this single bit

Performance of Channel Partitioning



Better system performance than the best previous scheduler at lower hardware cost

An Example of Bad Channel Partitioning

Combining Multiple Interference Control Techniques

- Combined interference control techniques can mitigate interference much more than a single technique alone can do

- The key challenge is:
  - Deciding what technique to apply when
  - Partitioning work appropriately between software and hardware

MCP and IMPS: Pros and Cons

- Upsides:
  - Keeps the memory scheduling hardware simple
  - Combines multiple interference reduction techniques
  - Can provide performance isolation across applications mapped to different channels
  - General idea of partitioning can be extended to smaller granularities in the memory hierarchy: banks, subarrays, etc.

- Downsides:
  - Reacting is difficult if workload changes behavior after profiling
  - Overhead of moving pages between channels restricts benefits

More on Memory Channel Partitioning

- Sai Prashanth Muralidhara, Lavanya Subramanian, Onur Mutlu, Mahmut Kandemir, and Thomas Moscibroda, **"Reducing Memory Interference in Multicore Systems via Application-Aware Memory Channel Partitioning"** *Proceedings of the 44th International Symposium on Microarchitecture (**MICRO**)*, Porto Alegre, Brazil, December 2011. Slides (pptx)

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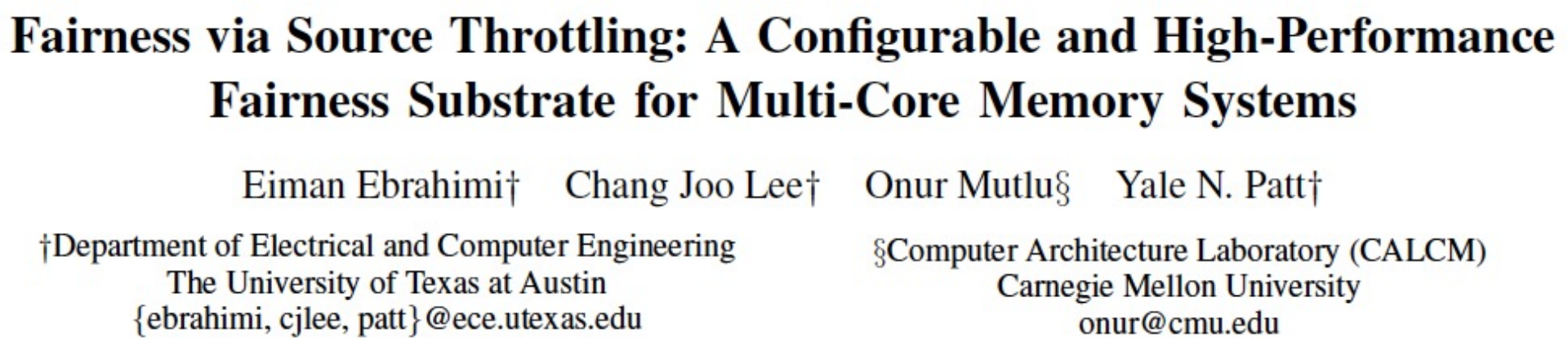
https://www.youtube.com/watch?v=yEYEzFwAY9g

Source Throttling

Eiman Ebrahimi, Chang Joo Lee, Onur Mutlu, and Yale N. Patt,
"Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems"
*Proceedings of the 15th International Conference on Architectural Support for Programming Languages and Operating Systems (**ASPLOS**)*, pages 335-346, Pittsburgh, PA, March 2010. Slides (pdf)
Best paper award.



Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems

Eiman Ebrahimi† Chang Joo Lee† Onur Mutlu§ Yale N. Patt†

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Fairness via Source Throttling

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FST ASPLOS 2010 Talk

Source Throttling: A Fairness Substrate

- Key idea: Manage inter-thread interference at the cores (sources), not at the shared resources

- Dynamically estimate unfairness in the memory system
- Feed back this information into a controller
- Throttle cores' memory access rates accordingly
  - Whom to throttle and by how much depends on performance target (throughput, fairness, per-thread QoS, etc)
  - E.g., if unfairness > system-software-specified target then throttle down core causing unfairness & throttle up core that was unfairly treated

- Ebrahimi et al., "Fairness via Source Throttling," ASPLOS'10, TOCS'12.

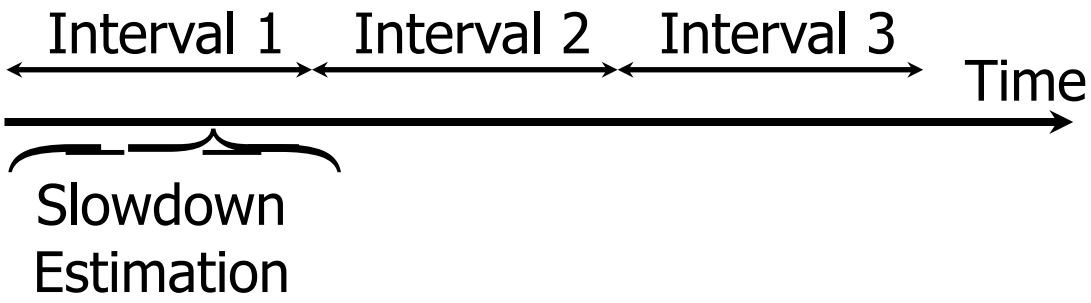
Fairness via Source Throttling (FST)

- Two components (interval-based)

- Run-time unfairness evaluation (in hardware)
  - Dynamically estimates the unfairness (application slowdowns) in the memory system
  - Estimates which application is slowing down which other

- Dynamic request throttling (hardware or software)
  - Adjusts how aggressively each core makes requests to the shared resources
  - Throttles down request rates of cores causing unfairness
    - Limit miss buffers, limit injection rate

Fairness via Source Throttling (FST) [ASPLOS'10]



FST

1- Estimating system unfairness
2- Find app. with the highest slowdown (App-slowest)
3- Find app. causing most interference for App-slowest (App-interfering)

```
if (Unfairness Estimate >Target)
{
 1-Throttle down App-interfering
   (limit injection rate and parallelism)
 2-Throttle up App-slowest
}
```

Dynamic Request Throttling

- Goal: Adjust how aggressively each core makes requests to the shared memory system

- Mechanisms:
  - Miss Status Holding Register (MSHR) quota
    - Controls the number of concurrent requests accessing shared resources from each application
  - Request injection frequency
    - Controls how often memory requests are issued to the last level cache from the MSHRs

Dynamic Request Throttling

- Throttling level assigned to each core determines both MSHR quota and request injection rate

Throttling level	MSHR quota	Request Injection Rate
100%	128	Every cycle
50%	64	Every other cycle
25%	32	Once every 4 cycles
10%	12	Once every 10 cycles
5%	6	Once every 20 cycles
4%	5	Once every 25 cycles
3%	3	Once every 30 cycles
2%	2	Once every 50 cycles

Total # of MSHRs: 128

System Software Support

- Different fairness objectives can be configured by system software
  - Keep maximum slowdown in check
    - Estimated Max Slowdown < Target Max Slowdown
  - Keep slowdown of particular applications in check to achieve a particular performance target
    - Estimated Slowdown(i) < Target Slowdown(i)

- Support for thread priorities
  - Weighted Slowdown(i) =
    Estimated Slowdown(i) x Weight(i)

Source Throttling Results: Takeaways

- Source throttling alone provides better performance than a combination of "smart" memory scheduling and fair caching
  - Decisions made at the memory scheduler and the cache sometimes contradict each other
- Neither source throttling alone nor "smart resources" alone provides the best performance
- Combined approaches are even more powerful
  - Source throttling and resource-based interference control

Source Throttling: Ups and Downs

- Advantages
  + Core/request throttling is easy to implement: no need to change the memory scheduling algorithm
  + Can be a general way of handling shared resource contention
  + Can reduce overall load/contention in the memory system

- Disadvantages
  - Requires slowdown estimations → difficult to estimate
  - Thresholds can become difficult to optimize
    → throughput loss due to too much throttling
    → can be difficult to find an overall-good configuration

More on Source Throttling (I)

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More on Source Throttling (II)

- Kevin Chang, Rachata Ausavarungnirun, Chris Fallin, and Onur Mutlu, **"HAT: Heterogeneous Adaptive Throttling for On-Chip Networks"**
  *Proceedings of the 24th International Symposium on Computer Architecture and High Performance Computing (**SBAC-PAD**)*, New York, NY, October 2012. Slides (pptx) (pdf)

HAT: Heterogeneous Adaptive Throttling for On-Chip Networks

Kevin Kai-Wei Chang, Rachata Ausavarungnirun, Chris Fallin, Onur Mutlu
Carnegie Mellon University
{kevincha,rachata,cfallin,onur}@cmu.edu

More on Source Throttling (III)

- George Nychis, Chris Fallin, Thomas Moscibroda, Onur Mutlu, and Srinivasan Seshan,
  "On-Chip Networks from a Networking Perspective: Congestion and Scalability in Many-core Interconnects"
  *Proceedings of the 2012 ACM SIGCOMM Conference (**SIGCOMM**)*, Helsinki, Finland, August 2012. Slides (pptx)

On-Chip Networks from a Networking Perspective: Congestion and Scalability in Many-Core Interconnects

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§ Microsoft Research Asia
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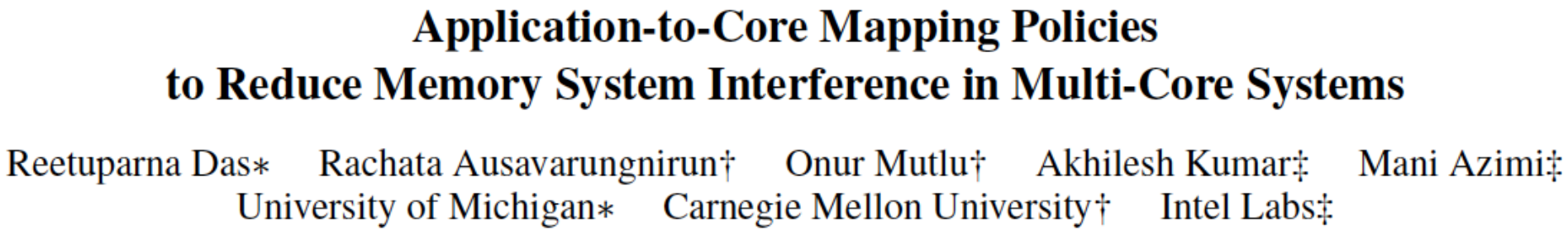
Application-to-Core Mapping to Reduce Interference

- Reetuparna Das, Rachata Ausavarungnirun, Onur Mutlu, Akhilesh Kumar, and Mani Azimi,
  "Application-to-Core Mapping Policies to Reduce Memory System Interference in Multi-Core Systems"
  *Proceedings of the 19th International Symposium on High-Performance Computer Architecture (**HPCA**)*, Shenzhen, China, February 2013.
  Slides (pptx)

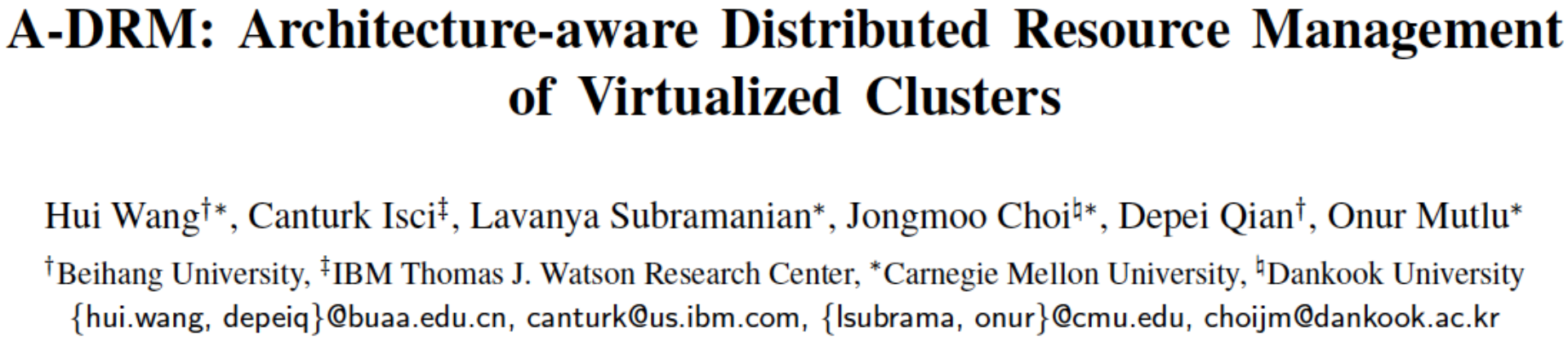


Application-to-Core Mapping Policies to Reduce Memory System Interference in Multi-Core Systems

Reetuparna Das* Rachata Ausavarungnirun† Onur Mutlu† Akhilesh Kumar‡ Mani Azimi‡
University of Michigan* Carnegie Mellon University† Intel Labs‡

Architecture-Aware DRM

- Hui Wang, Canturk Isci, Lavanya Subramanian, Jongmoo Choi, Depei Qian, and Onur Mutlu,
  "A-DRM: Architecture-aware Distributed Resource Management of Virtualized Clusters"
  *Proceedings of the 11th ACM SIGPLAN/SIGOPS International Conference on Virtual Execution Environments (**VEE**)*, Istanbul, Turkey, March 2015.
  [Slides (pptx) (pdf)]



A-DRM: Architecture-aware Distributed Resource Management of Virtualized Clusters

Hui Wang[†*], Canturk Isci[‡], Lavanya Subramanian[*], Jongmoo Choi[♮*], Depei Qian[†], Onur Mutlu[*]
[†]Beihang University, [‡]IBM Thomas J. Watson Research Center, [*]Carnegie Mellon University, [♮]Dankook University
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Summary

Summary: Fundamental Interference Control Techniques

- Goal: to reduce/control interference

1. Prioritization or request scheduling
2. Data mapping to banks/channels/ranks
3. Core/source throttling
4. Application/thread scheduling

Best is to combine all. How would you do that?

Summary: Memory QoS Approaches and Techniques

- Approaches: Smart vs. dumb resources
  - Smart resources: QoS-aware memory scheduling
  - Dumb resources: Source throttling; channel partitioning
  - Both approaches are effective at reducing interference
  - No single best approach for all workloads
- Techniques: Request/thread scheduling, source throttling, memory partitioning
  - All approaches are effective at reducing interference
  - Can be applied at different levels: hardware vs. software
  - No single best technique for all workloads
- Combined approaches and techniques are the most powerful
  - Integrated Memory Channel Partitioning and Scheduling [MICRO'11]

Summary: Memory Interference and QoS

- QoS-unaware memory → uncontrollable and unpredictable system
- Providing QoS awareness improves performance, predictability, fairness, and utilization of the memory system
- Discussed many new techniques to:
  - Minimize memory interference
  - Provide predictable performance
- Many new research ideas needed for integrated techniques and closing the interaction with software

What Did We Not Cover?

- Prefetch-aware shared resource management
- DRAM-controller co-design
- Cache interference management
- Interconnect interference management
- Write-read scheduling
- DRAM designs to reduce interference
- Interference & QoS in processing-in-memory
- …

What the Future May Bring

- Memory QoS techniques for heterogeneous SoC systems
  - Many accelerators, processing in/near memory, better predictability, higher performance
- Combinations of memory QoS/performance techniques
  - E.g., data mapping and scheduling
- **Use of machine learning techniques to manage resources**
- Real prototypes

Computer Architecture

Lecture 13a: Memory Controllers: Service Quality

Ataberk Olgun
Prof. Onur Mutlu
ETH Zürich

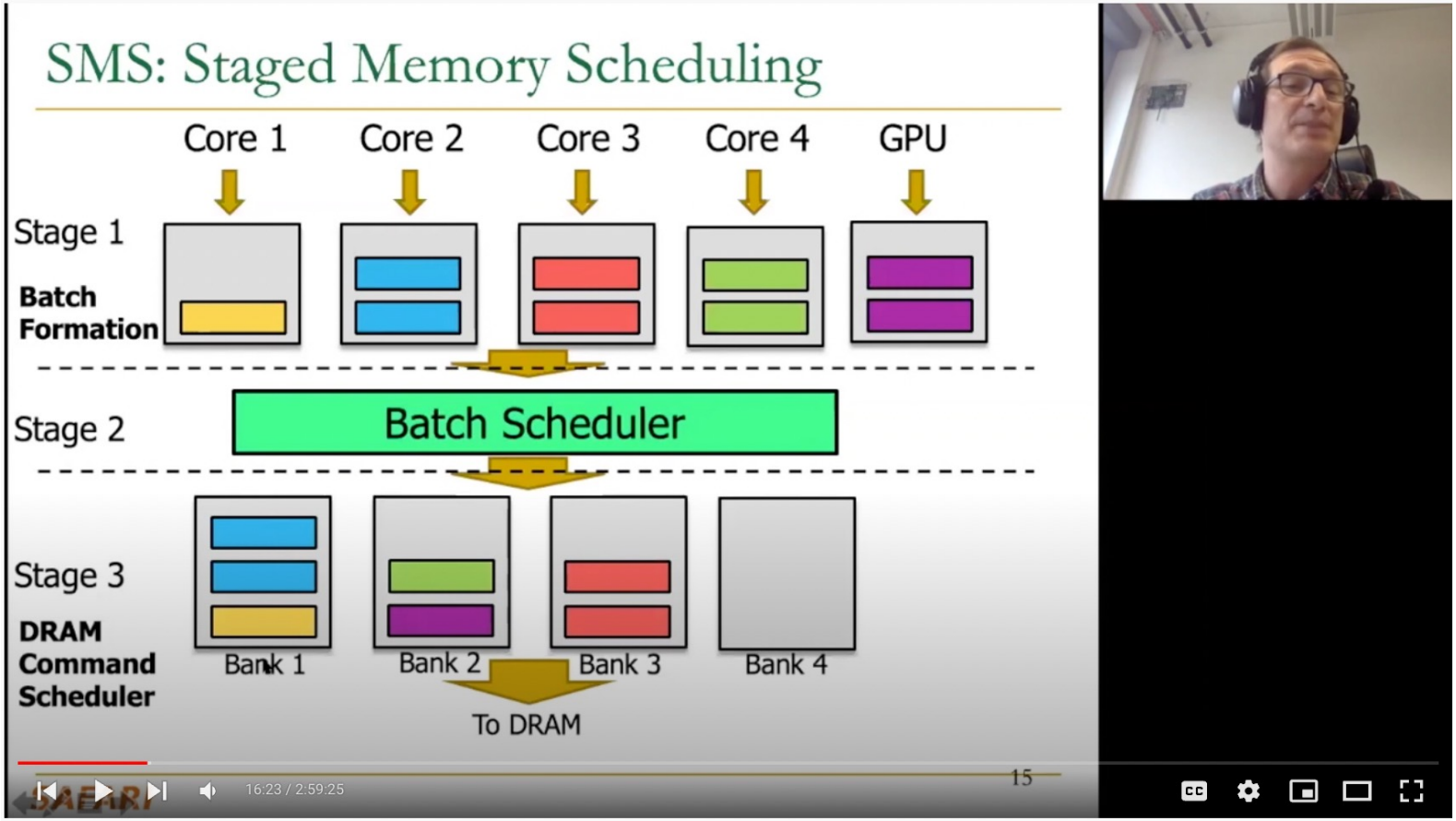
Fall 2023

9 November 2023

Backup Slides

Memory Scheduling for Heterogeneous Systems

Lecture on Heterogeneous System Scheduling



https://www.youtube.com/watch?v=Axye9VqQT7w&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=26

Staged Memory Scheduling

Rachata Ausavarungnirun, Kevin Chang, Lavanya Subramanian, Gabriel Loh, and Onur Mutlu,

"Staged Memory Scheduling: Achieving High Performance and Scalability in Heterogeneous Systems"

39th International Symposium on Computer Architecture (***ISCA***),

Portland, OR, June 2012.

SMS ISCA 2012 Talk

SMS: Executive Summary

- **Observation:** Heterogeneous CPU-GPU systems require memory schedulers with large request buffers
- **Problem:** Existing monolithic application-aware memory scheduler designs are hard to scale to large request buffer sizes
- **Solution:** Staged Memory Scheduling (SMS)

  decomposes the memory controller into three simple stages:

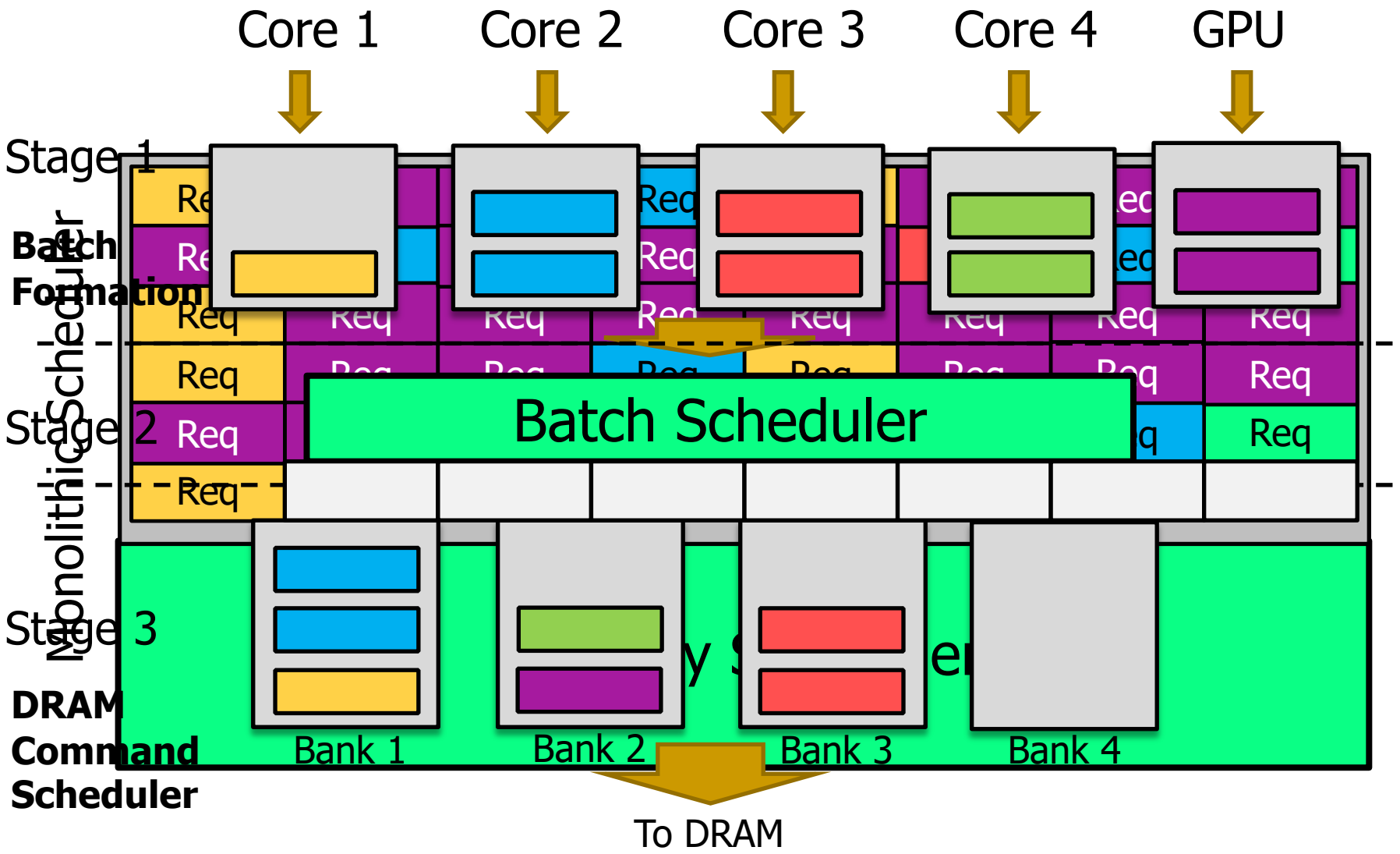
  1) Batch formation: maintains row buffer locality

  2) Batch scheduler: reduces interference between applications

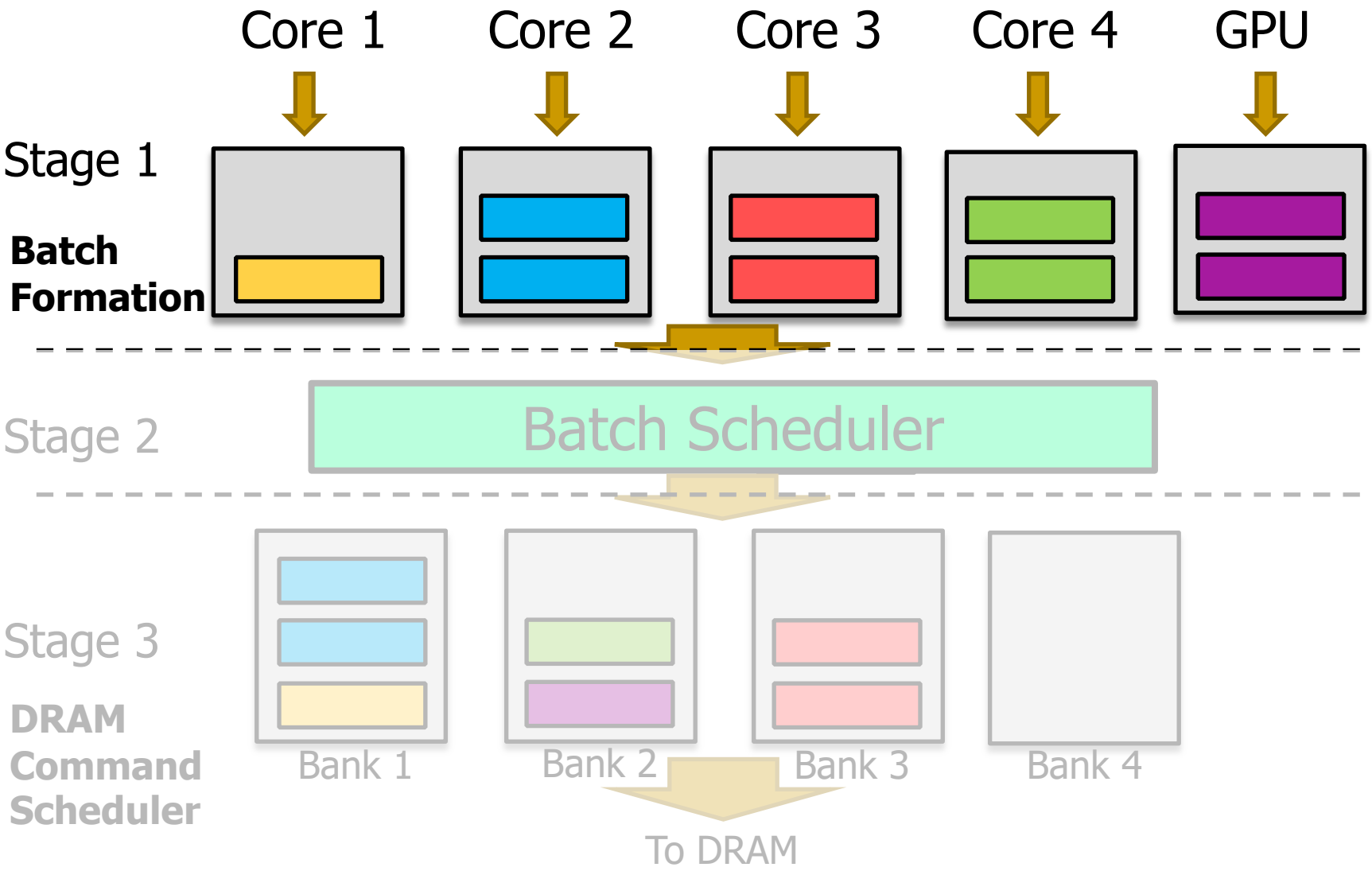
  3) DRAM command scheduler: issues requests to DRAM

- Compared to state-of-the-art memory schedulers:
  - SMS is significantly simpler and more scalable
  - SMS provides higher performance and fairness

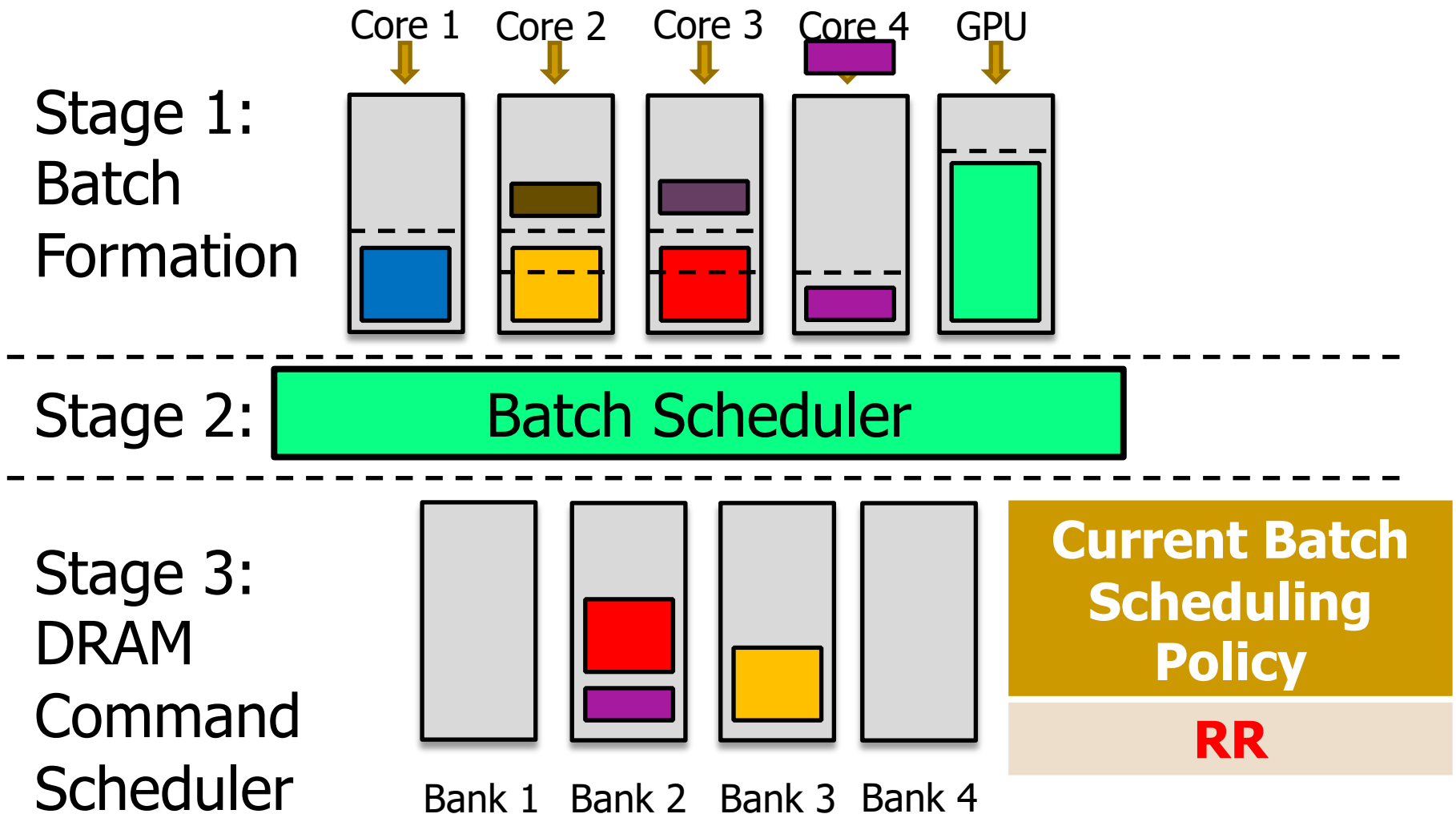
SMS: Staged Memory Scheduling



SMS: Staged Memory Scheduling



Putting Everything Together



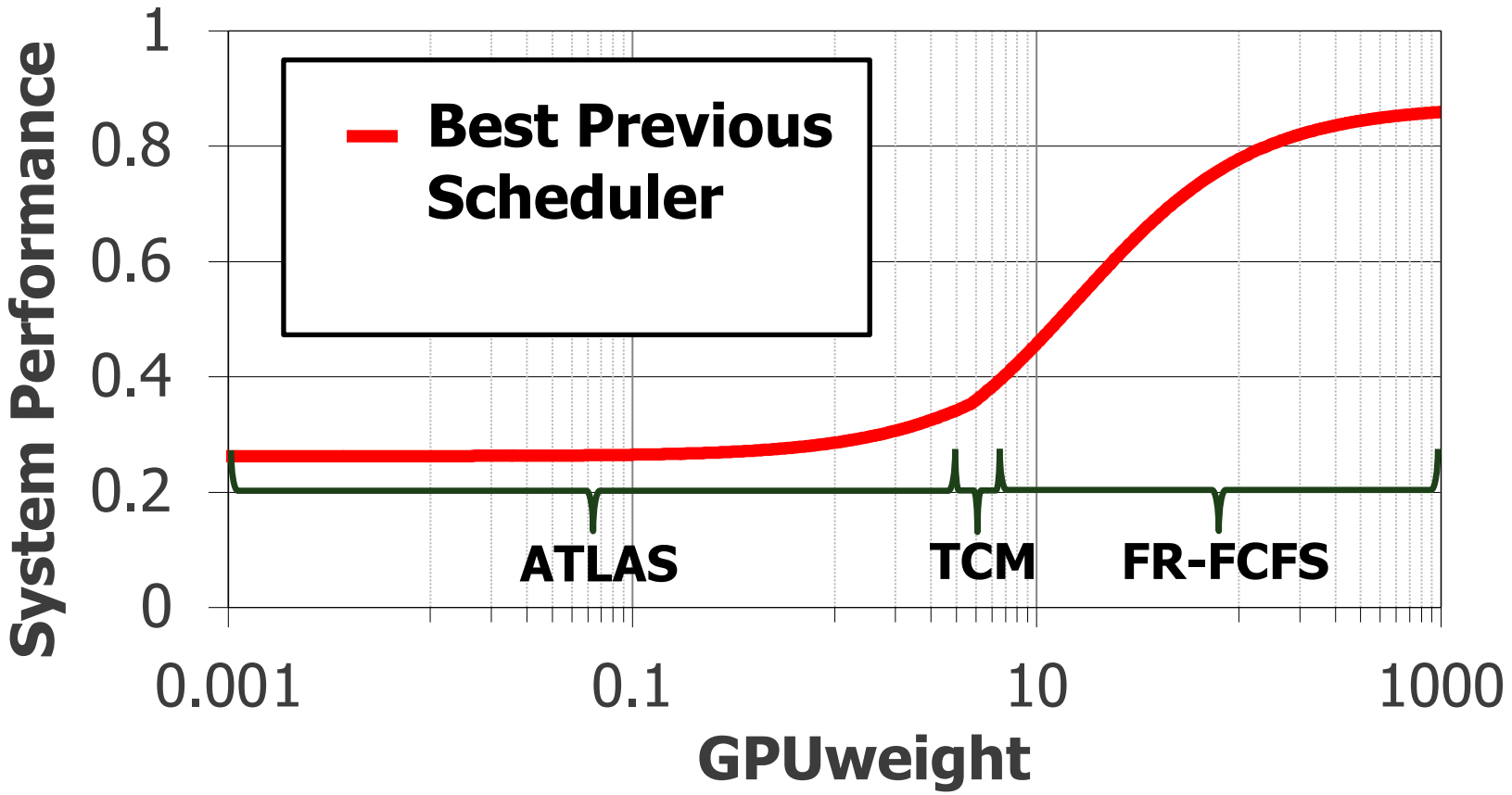
Complexity

- Compared to a row hit first scheduler, SMS consumes*
  - 66% less area
  - 46% less static power

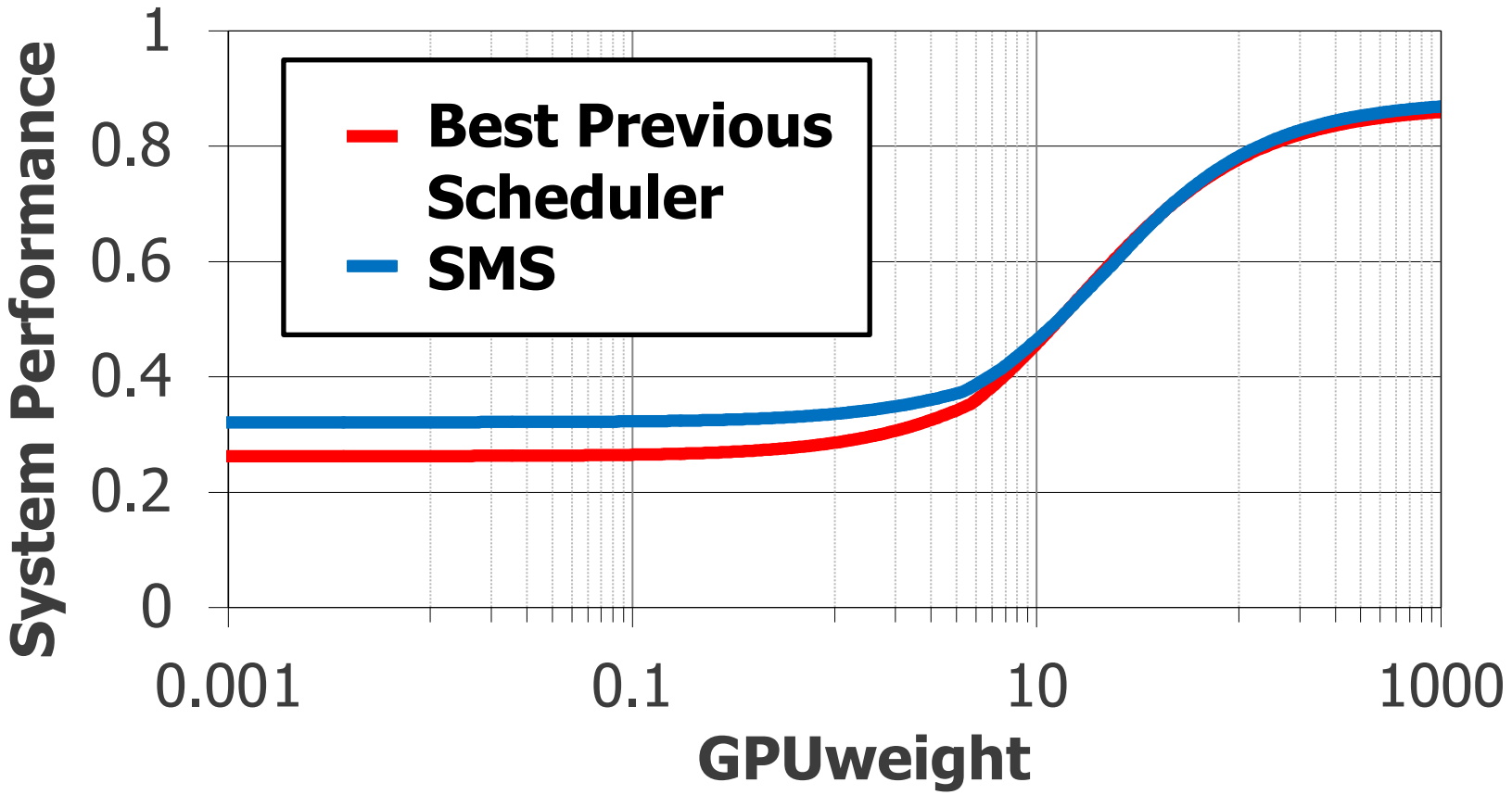
- Reduction comes from:
  - Monolithic scheduler → stages of simpler schedulers
  - Each stage has a simpler scheduler (considers fewer properties at a time to make the scheduling decision)
  - Each stage has simpler buffers (FIFO instead of out-of-order)
  - Each stage has a portion of the total buffer size (buffering is distributed across stages)

*** Based on a Verilog model using 180nm library**

Performance at Different GPU Weights



Performance at Different GPU Weights



- At every GPU weight, SMS outperforms the best previous scheduling algorithm for that weight

More on SMS

- Rachata Ausavarungnirun, Kevin Chang, Lavanya Subramanian, Gabriel Loh, and Onur Mutlu,
  "Staged Memory Scheduling: Achieving High Performance and Scalability in Heterogeneous Systems"
  *Proceedings of the 39th International Symposium on Computer Architecture (**ISCA**)*, Portland, OR, June 2012. Slides (pptx)

Staged Memory Scheduling: Achieving High Performance and Scalability in Heterogeneous Systems

Rachata Ausavarungnirun[†] Kevin Kai-Wei Chang[†] Lavanya Subramanian[†] Gabriel H. Loh[‡] Onur Mutlu[†]

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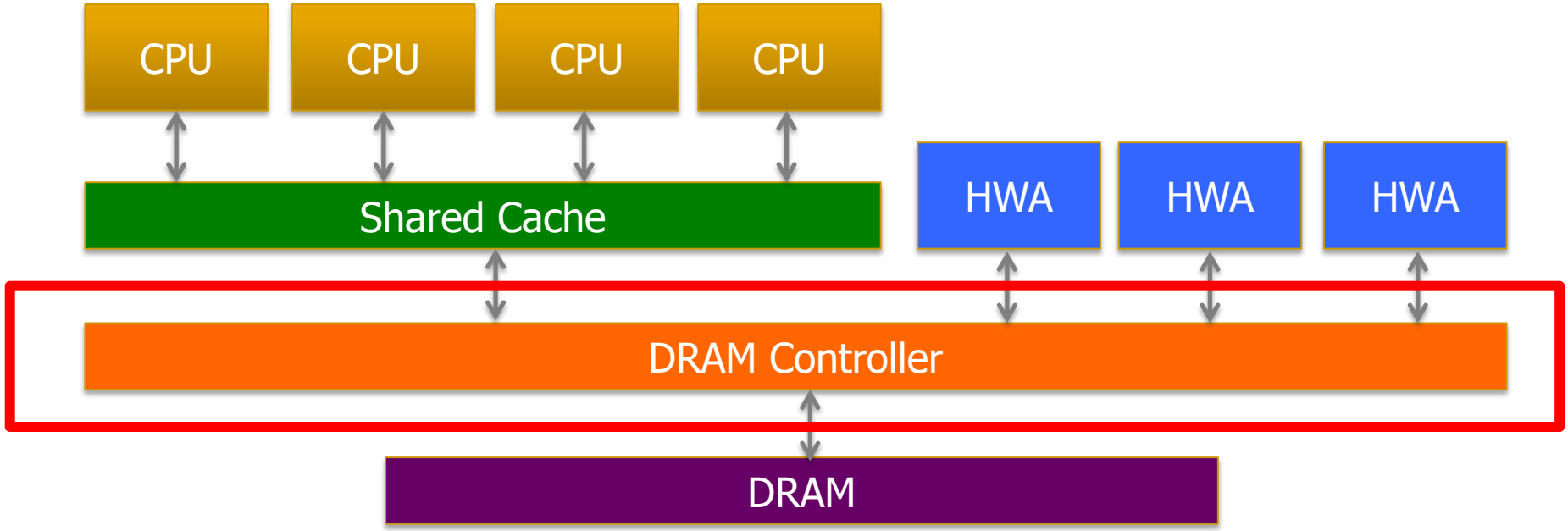
DASH Memory Scheduler

[TACO 2016]

Current SoC Architectures



- Heterogeneous agents: CPUs and HWAs
  - HWA : Hardware Accelerator
- Main memory is shared by CPUs and HWAs → Interference

How to schedule memory requests from CPUs and HWAs to mitigate interference?

DASH Scheduler: Executive Summary

- Problem: Hardware accelerators (HWAs) and CPUs share the same memory subsystem and interfere with each other in main memory
- Goal: Design a memory scheduler that improves CPU performance while meeting HWAs' deadlines
- Challenge: Different HWAs have different memory access characteristics and different deadlines, which current schedulers do not smoothly handle
  - Memory-intensive and long-deadline HWAs significantly degrade CPU performance *when they become high priority* (due to slow progress)
  - Short-deadline HWAs sometimes miss their deadlines *despite high priority*
- Solution: DASH Memory Scheduler
  - Prioritize HWAs over CPU anytime when the HWA is not making good progress
  - Application-aware scheduling for CPUs and HWAs
- Key Results:

  1) Improves CPU performance for a wide variety of workloads by 9.5%

  2) Meets 100% deadline met ratio for HWAs
- DASH source code freely available on our GitHub

Goal of Our Scheduler (DASH)

- Goal: Design a memory scheduler that
  - Meets GPU/accelerators' frame rates/deadlines *and*
  - Achieves high CPU performance

- Basic Idea:
  - *Different CPU applications and hardware accelerators have different memory requirements*
  - Track progress of different agents and prioritize accordingly

Key Observation: Distribute Priority for Accelerators

- GPU/accelerators need priority to meet deadlines
- Worst case prioritization not always the best
- Prioritize when they are **not** on track to meet a deadline

Distributing priority over time mitigates impact of accelerators on CPU cores' requests

Key Observation: Not All Accelerators are Equal

- **Long-deadline** accelerators are more likely to **meet** their deadlines
- **Short-deadline** accelerators are more likely to **miss** their deadlines

Schedule short-deadline accelerators based on worst-case memory access time

Key Observation: Not All CPU cores are Equal

- **Memory-intensive** cores are much **less vulnerable** to interference
- **Memory non-intensive** cores are much **more vulnerable** to interference

Prioritize accelerators over memory-intensive cores to ensure accelerators do not become urgent

DASH Summary: Key Ideas and Results

- *Distribute priority for HWAs*
- *Prioritize HWAs over memory-intensive CPU cores even when not urgent*
- *Prioritize short-deadline-period HWAs based on worst case estimates*

Improves CPU performance by 7-21%
Meets (almost) 100% of deadlines for HWAs

DASH: Scheduling Policy

- DASH scheduling policy
  1. Short-deadline-period HWAs with high priority
  2. Long-deadline-period HWAs with high priority
  3. Memory non-intensive CPU applications
  4. Long-deadline-period HWAs with low priority
  5. Memory-intensive CPU applications
  6. Short-deadline-period HWAs with low priority

Switch probabilistically

More on DASH

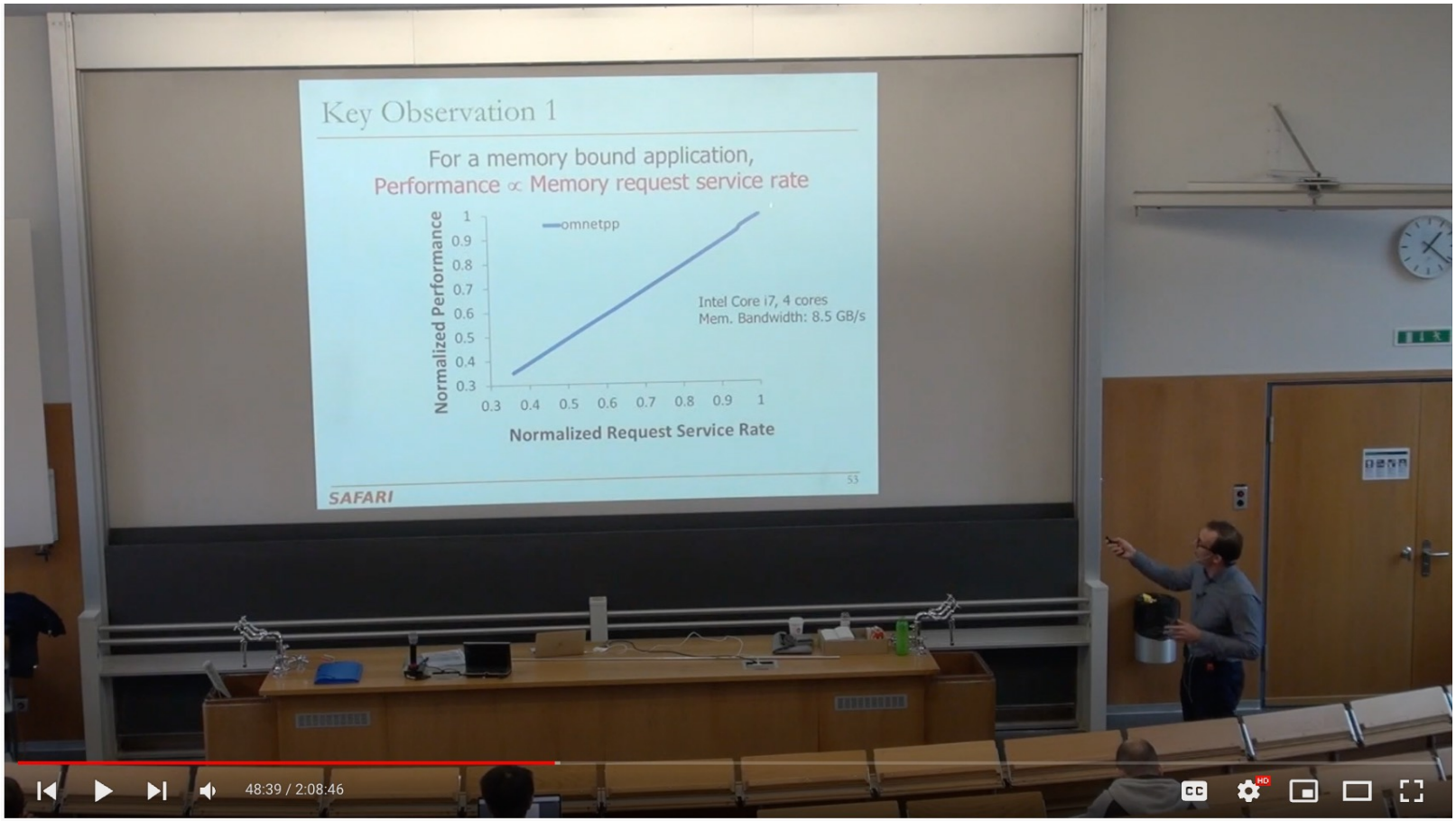
- Hiroyuki Usui, Lavanya Subramanian, Kevin Kai-Wei Chang, and Onur Mutlu,
  "DASH: Deadline-Aware High-Performance Memory Scheduler for Heterogeneous Systems with Hardware Accelerators"
  ACM Transactions on Architecture and Code Optimization (***TACO***),
  Vol. 12, January 2016.
  Presented at the 11th HiPEAC Conference, Prague, Czech Republic, January 2016.
  [Slides (pptx) (pdf)]
  [Source Code]

DASH: Deadline-Aware High-Performance Memory Scheduler for Heterogeneous Systems with Hardware Accelerators

HIROYUKI USUI, LAVANYA SUBRAMANIAN, KEVIN KAI-WEI CHANG,
and ONUR MUTLU, Carnegie Mellon University

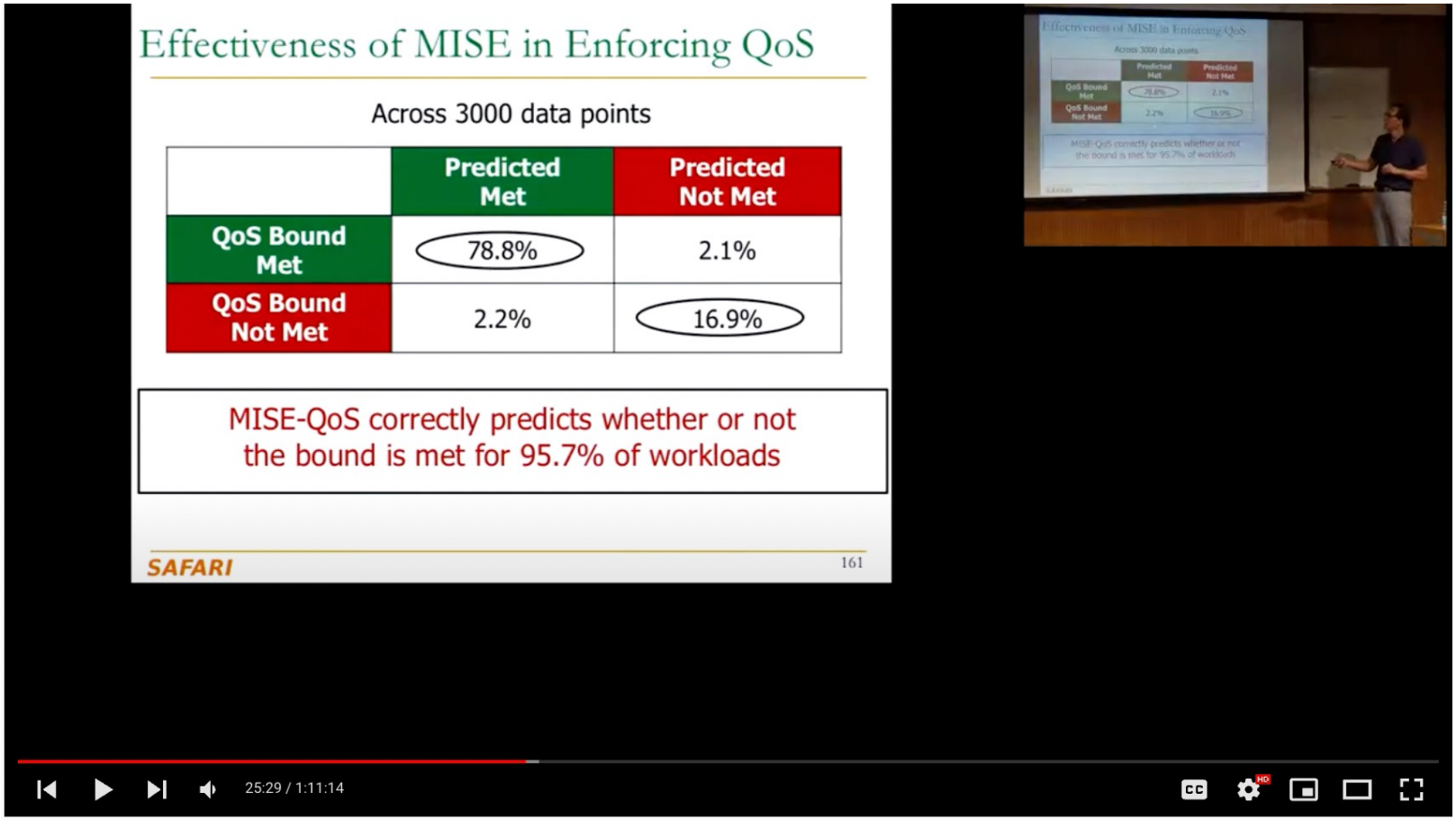
Predictable Performance: Strong Memory Service Guarantees

Lecture on Predictable Performance



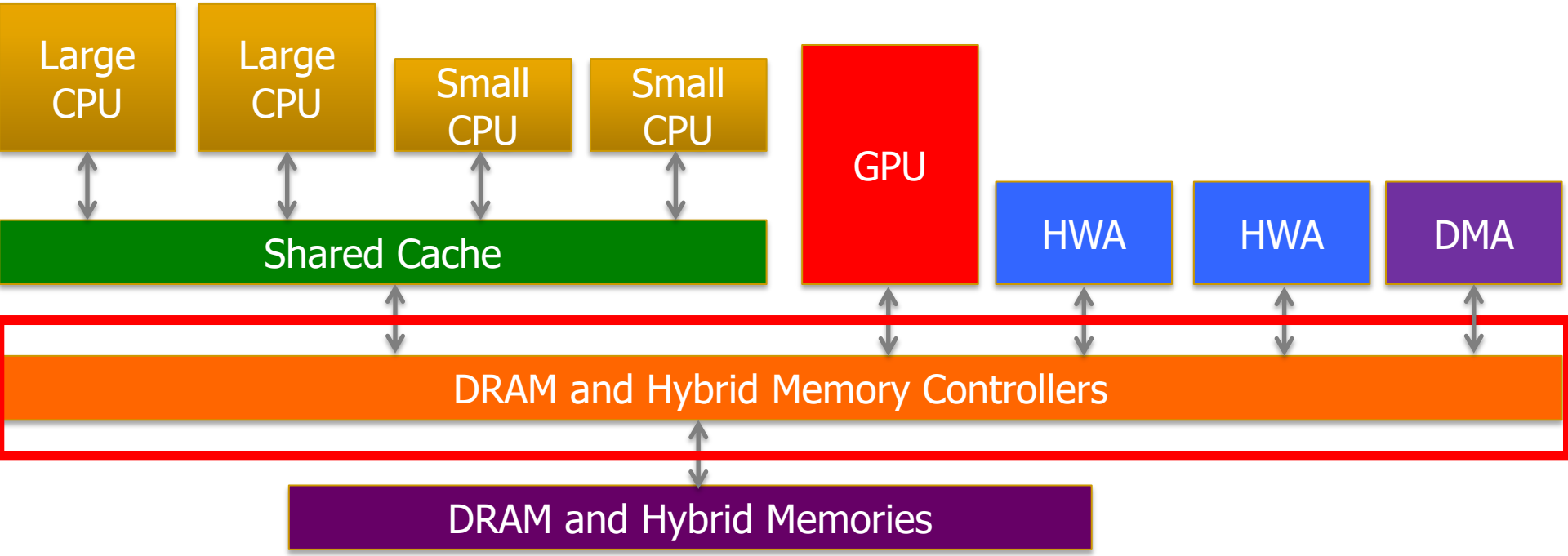
https://www.youtube.com/watch?v=Axye9VqQT7w&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=26

Lecture on Predictable Performance



https://www.youtube.com/watch?v=15hRJLhGWGA&list=PL5Q2soXY2Zi-IymxXpH_9vlZCOeA7Yfn9&index=19

Goal: Predictable Performance in Complex Systems



- Heterogeneous agents: CPUs, GPUs, HWAs, DMA engine, …
- Memory resources shared by CPUs/GPUs/HWAs → Interference

How to allocate resources to heterogeneous agents to mitigate interference and provide predictable performance?

Strong Memory Service Guarantees

- Goal: Satisfy performance/SLA requirements in the presence of shared main memory, heterogeneous agents, and hybrid memory/storage

- Approach:
  - Develop techniques/models to accurately estimate the performance loss of an application/agent in the presence of resource sharing
  - Develop mechanisms (hardware and software) to enable the resource partitioning/prioritization needed to achieve the required performance levels for all applications
  - All the while providing high system performance

- Subramanian et al., "MISE: Providing Performance Predictability and Improving Fairness in Shared Main Memory Systems," HPCA 2013.
- Subramanian et al., "The Application Slowdown Model," MICRO 2015.

Predictable Performance Readings (I)

Eiman Ebrahimi, Chang Joo Lee, Onur Mutlu, and Yale N. Patt,
"Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems"
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Predictable Performance Readings (II)

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MISE: Providing Performance Predictability and Improving Fairness in Shared Main Memory Systems

Lavanya Subramanian Vivek Seshadri Yoongu Kim Ben Jaiyen Onur Mutlu

Carnegie Mellon University

Predictable Performance Readings (III)

- Lavanya Subramanian, Vivek Seshadri, Arnab Ghosh, Samira Khan, and Onur Mutlu,
  "The Application Slowdown Model: Quantifying and Controlling the Impact of Inter-Application Interference at Shared Caches and Main Memory"
  *Proceedings of the 48th International Symposium on Microarchitecture (**MICRO**)*, Waikiki, Hawaii, USA, December 2015.
  [Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)] [Poster (pptx) (pdf)]
  [Source Code]

The Application Slowdown Model: Quantifying and Controlling the Impact of Inter-Application Interference at Shared Caches and Main Memory

Lavanya Subramanian*§ Vivek Seshadri* Arnab Ghosh*†
Samira Khan*‡ Onur Mutlu*

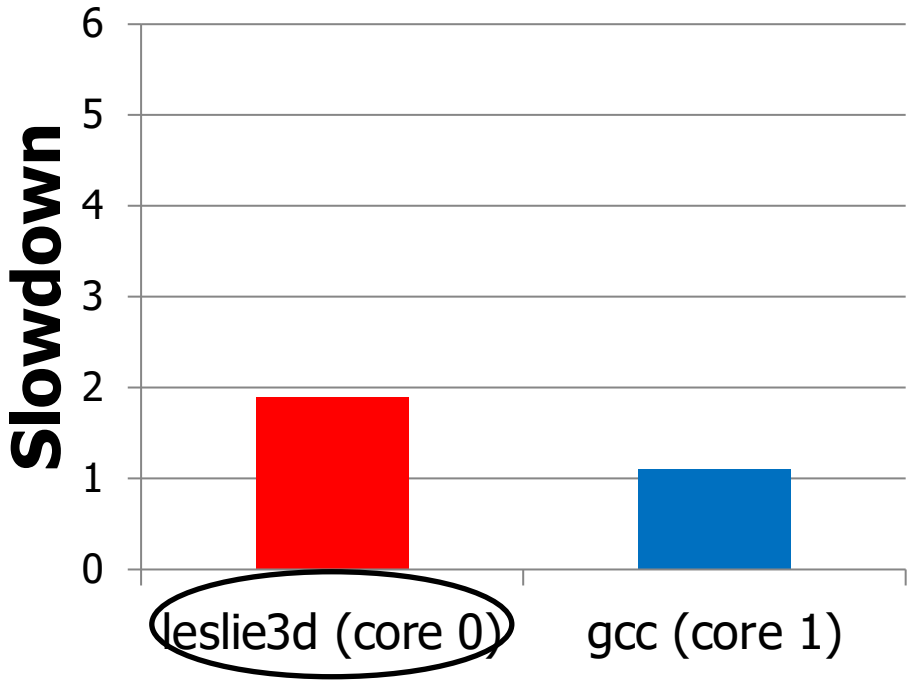
*Carnegie Mellon University §Intel Labs †IIT Kanpur ‡University of Virginia

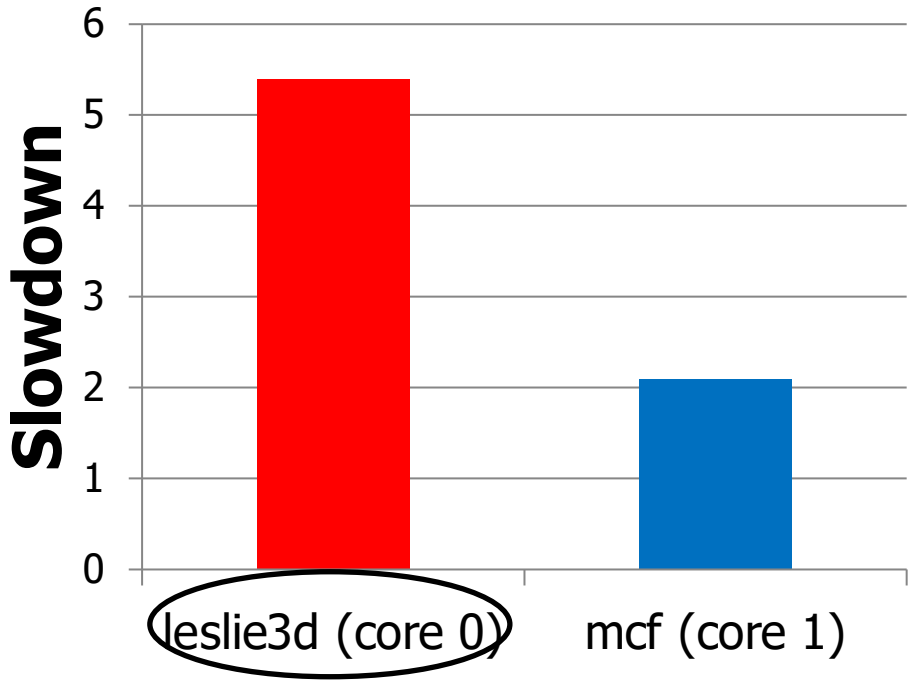
MISE: Providing Performance Predictability in Shared Main Memory Systems

Lavanya Subramanian, Vivek Seshadri,
Yoongu Kim, Ben Jaiyen, Onur Mutlu

SAFARI Carnegie Mellon

Unpredictable Application Slowdowns





An application's performance depends on which application it is running with

Need for Predictable Performance

- There is a need for predictable performance
  - When multiple applications share resources
  - Especially if some applications require performance

Our Goal: Predictable performance in the presence of memory interference

- Example 2: In server systems
  - Different users' jobs consolidated onto the same server
  - Need to provide bounded slowdowns to critical jobs

Outline

1. Estimate Slowdown

2. Control Slowdown

Outline

1. Estimate Slowdown

- Key Observations
- Implementation
- MISE Model: Putting it All Together
- Evaluating the Model

2. Control Slowdown

- Providing Soft Slowdown Guarantees
- Minimizing Maximum Slowdown

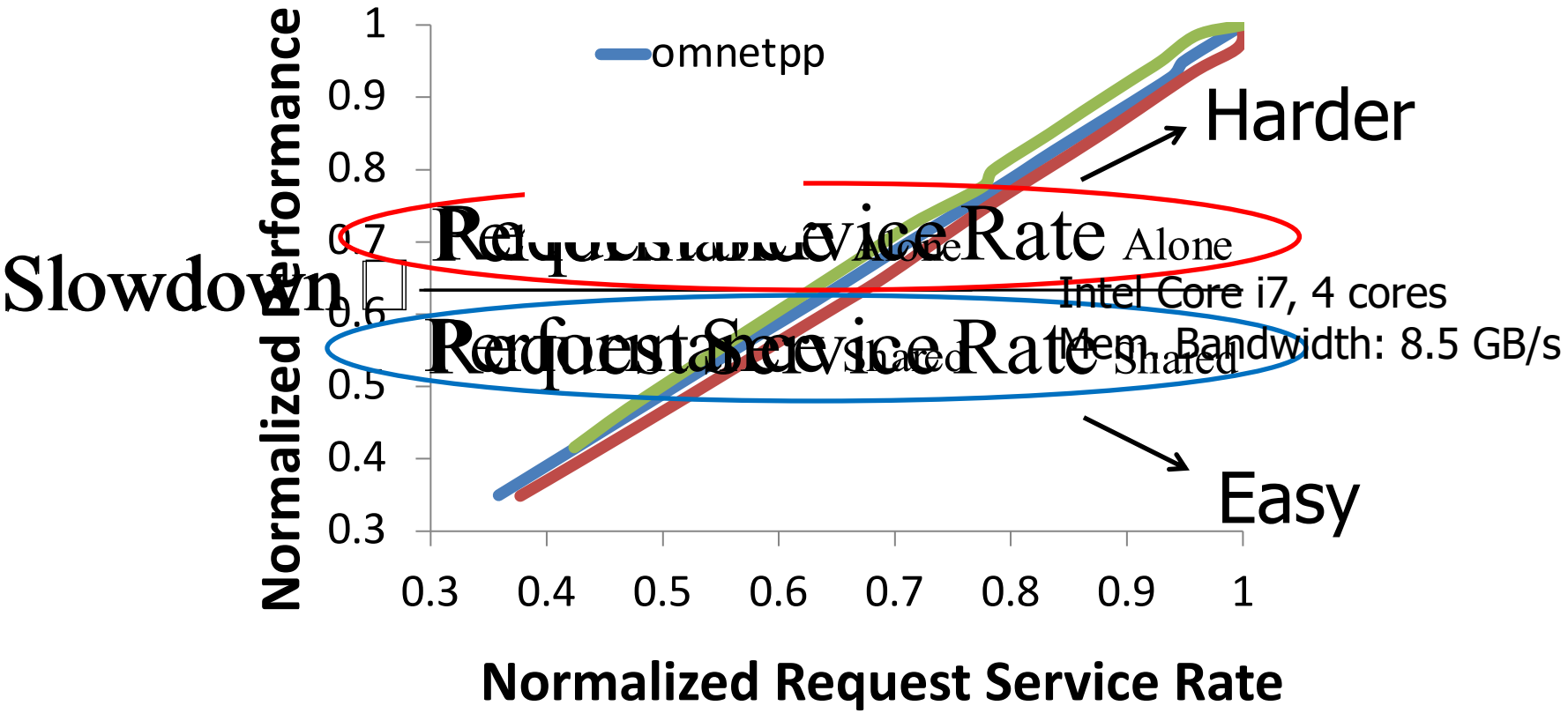
Slowdown: Definition

$$\text{Slowdown} = \frac{\text{Performance Alone}}{\text{Performance Shared}}$$

Key Observation 1

For a memory bound application,

Performance ∝ Memory request service rate



Key Observation 2

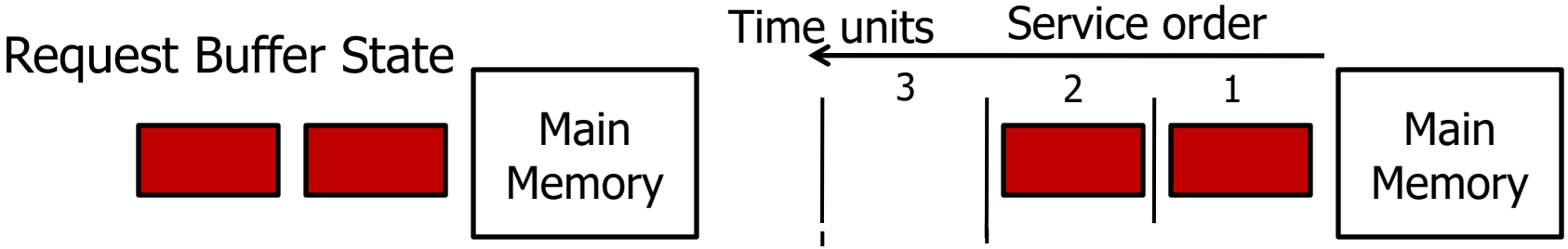
Request Service Rate $_{Alone}$ (RSR_{Alone}) of an application can be estimated by giving the application highest priority in accessing memory

Highest priority → Little interference

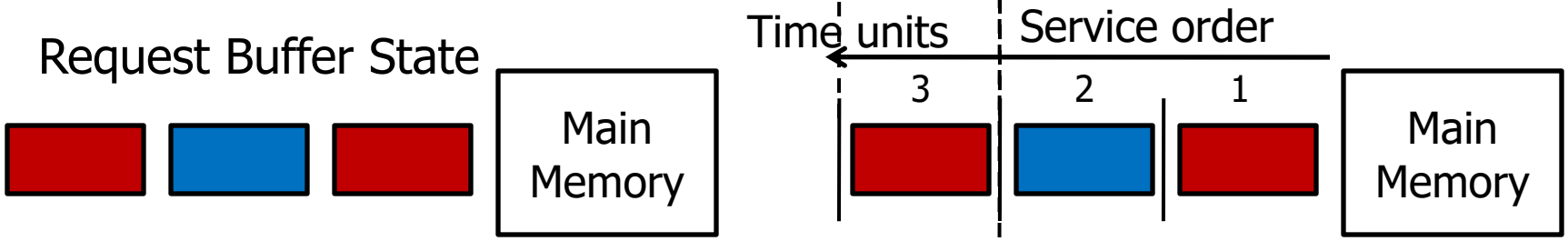
(almost as if the application were run alone)

Key Observation 2

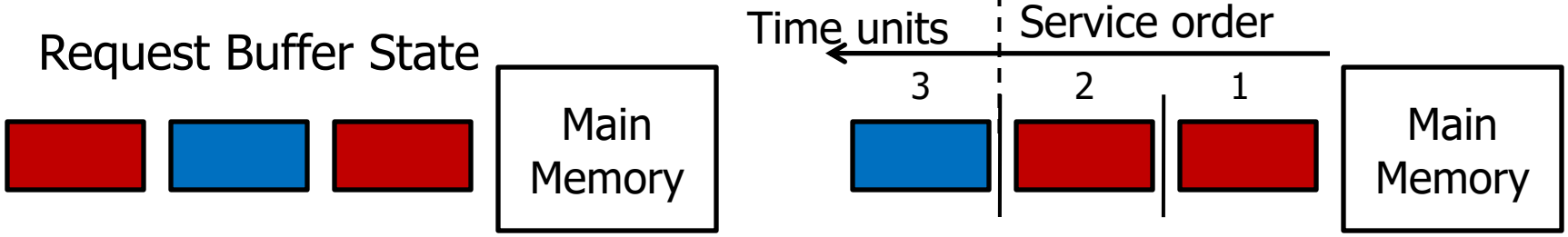
1. Run alone



2. Run with another application



3. Run with another application: highest priority

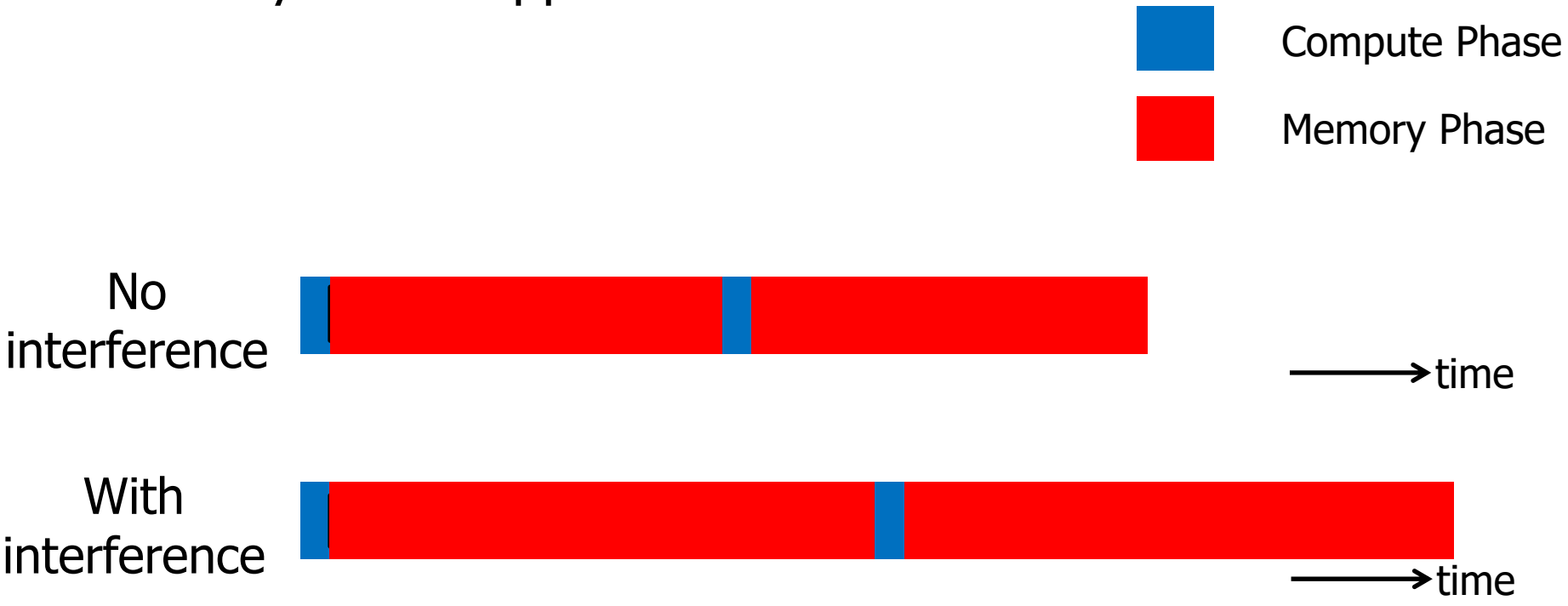


Memory Interference-induced Slowdown Estimation (MISE) model for memory bound applications

$$\text{Slowdown} \propto \frac{\text{Request Service Rate}_{\text{Alone}} (\text{RSR}_{\text{Alone}})}{\text{Request Service Rate}_{\text{Shared}} (\text{RSR}_{\text{Shared}})}$$

Key Observation 3

- Memory-bound application



Memory phase slowdown dominates overall slowdown

Key Observation 3

Memory Interference-induced Slowdown Estimation (MISE) model for non-memory bound applications

$$\text{Slowdown} \propto (1-\alpha) + \alpha \frac{\text{RSR}_{\text{Alone}}}{\text{RSR}_{\text{Shared}}}$$

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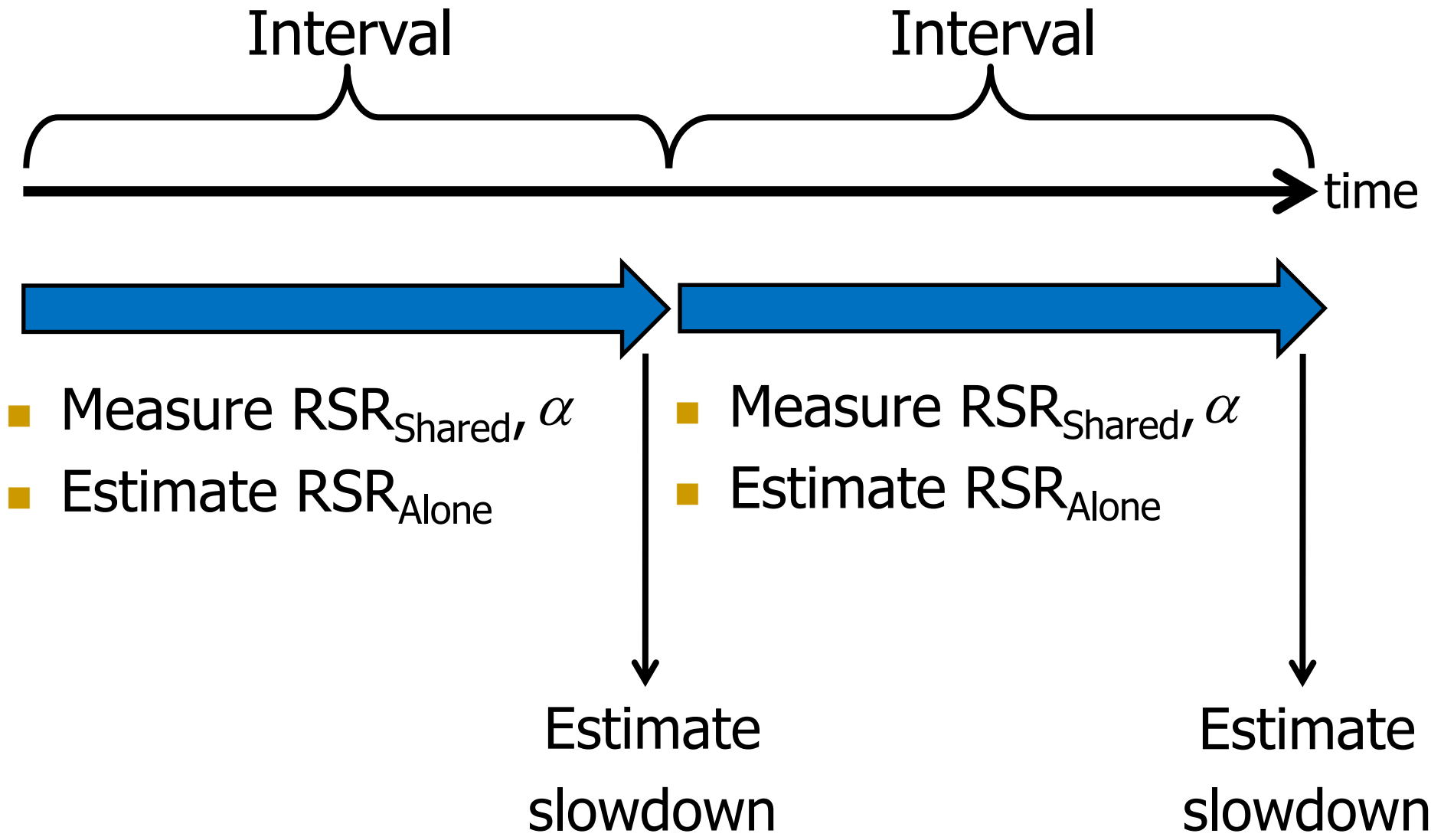
Interval Based Operation



Measuring RSR_{Shared} and α

- Request Service Rate $_{Shared}$ (RSR_{Shared})
  - Per-core counter to track number of requests serviced
  - At the end of each interval, measure

$$RSR_{Shared} = \frac{\text{Number of Requests Serviced}}{\text{Interval Length}}$$

- Memory Phase Fraction (α)
  - Count number of stall cycles at the core
  - Compute fraction of cycles stalled for memory

Estimating Request Service Rate $_{Alone}$ (RSR_{Alone})

- Divide each interval into shorter epochs
- At the beginning of each epoch
  - Memory controller randomly picks an application as the highest priority application
- At the end of an interval, for each application, estimate

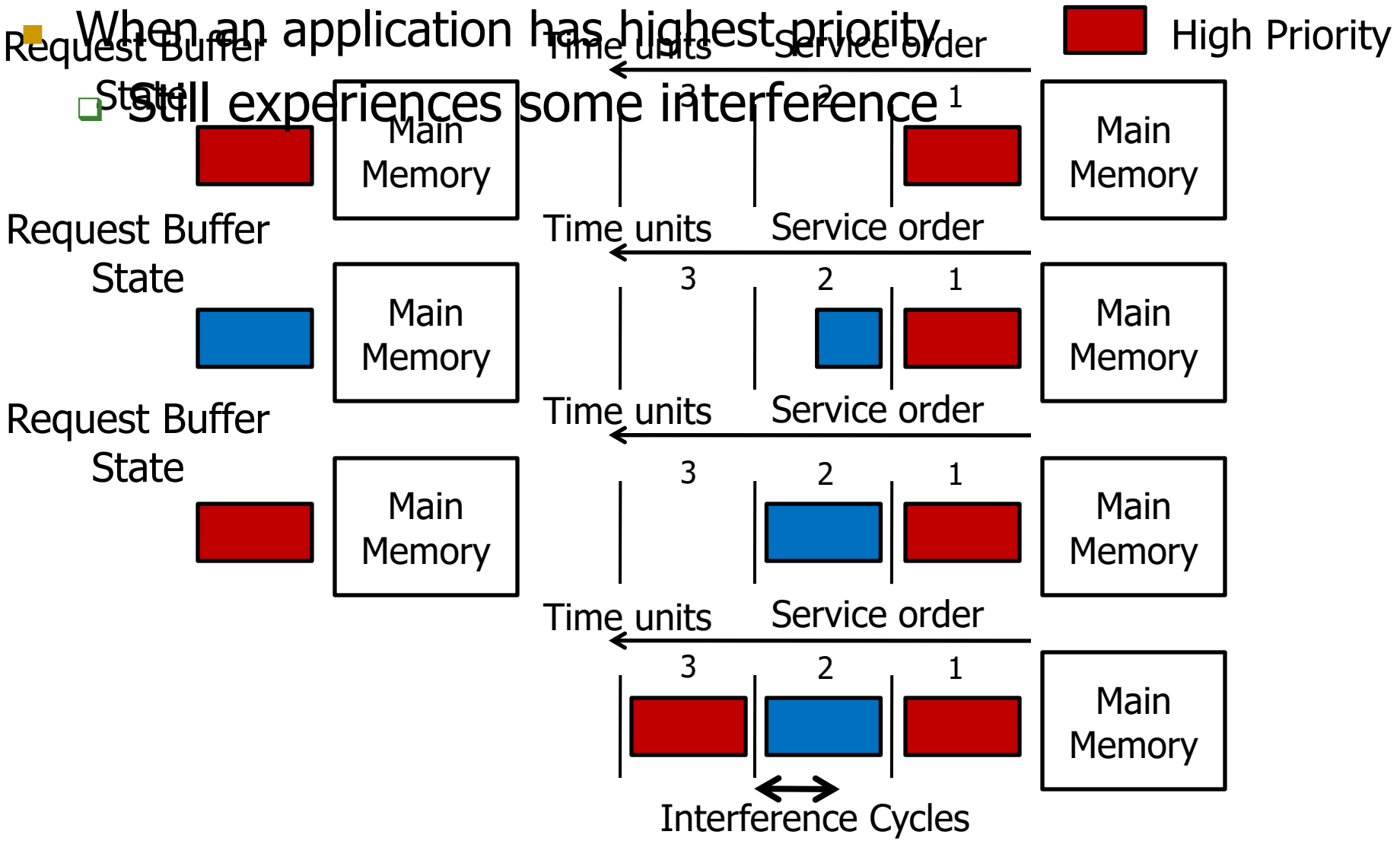
Goal: Estimate RSR_{Alone}

How: Periodically give each application highest priority in accessing memory

$$RSR_{Alone} \approx \frac{\text{Number of Requests During High Priority Epochs}}{\text{Number of Cycles Application Given High Priority}}$$

Inaccuracy in Estimating RSR_{Alone}

- When an application has highest priority
  - Still experiences some interference



Accounting for Interference in RSR_{Alone} Estimation

- Solution: Determine and remove interference cycles from RSR_{Alone} calculation

$$RSR_{Alone} = \frac{\text{Number of Requests During High Priority Epochs}}{\text{Number of Cycles Application Given High Priority} - \text{Interference Cycles}}$$

- A cycle is an interference cycle if
  - a request from the highest priority application is waiting in the request buffer *and*
  - another application's request was issued previously

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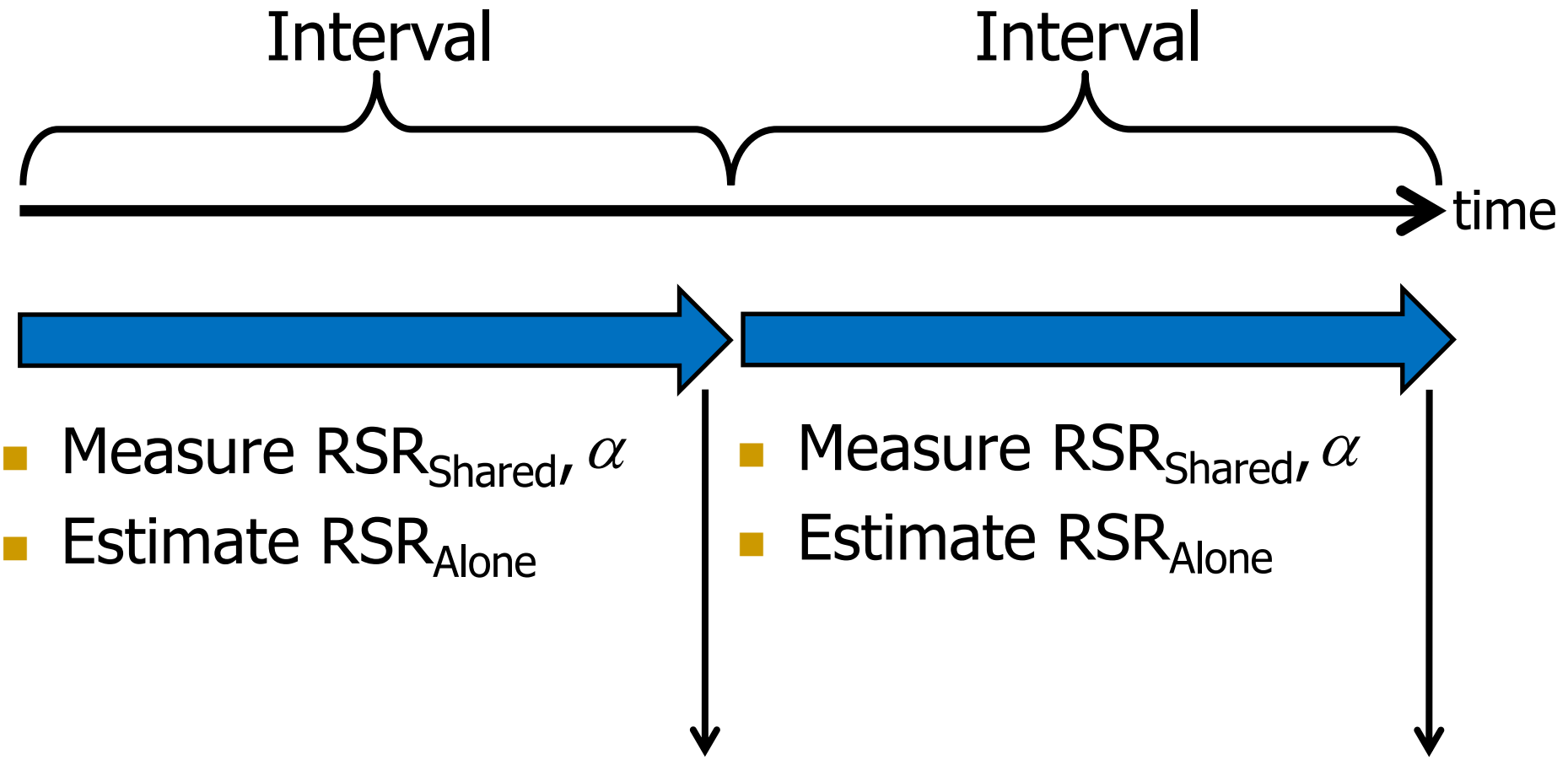
MISE Model: Putting it All Together



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Previous Work on Slowdown Estimation

- Previous work on slowdown estimation
  - **STFM** (Stall Time Fair Memory) Scheduling [Mutlu+, MICRO '07]
  - **FST** (Fairness via Source Throttling) [Ebrahimi+, ASPLOS '10]
  - **Per-thread Cycle Accounting** [Du Bois+, HiPEAC '13]

- Basic Idea:

Count number of cycles application receives interference

Two Major Advantages of MISE Over STFM

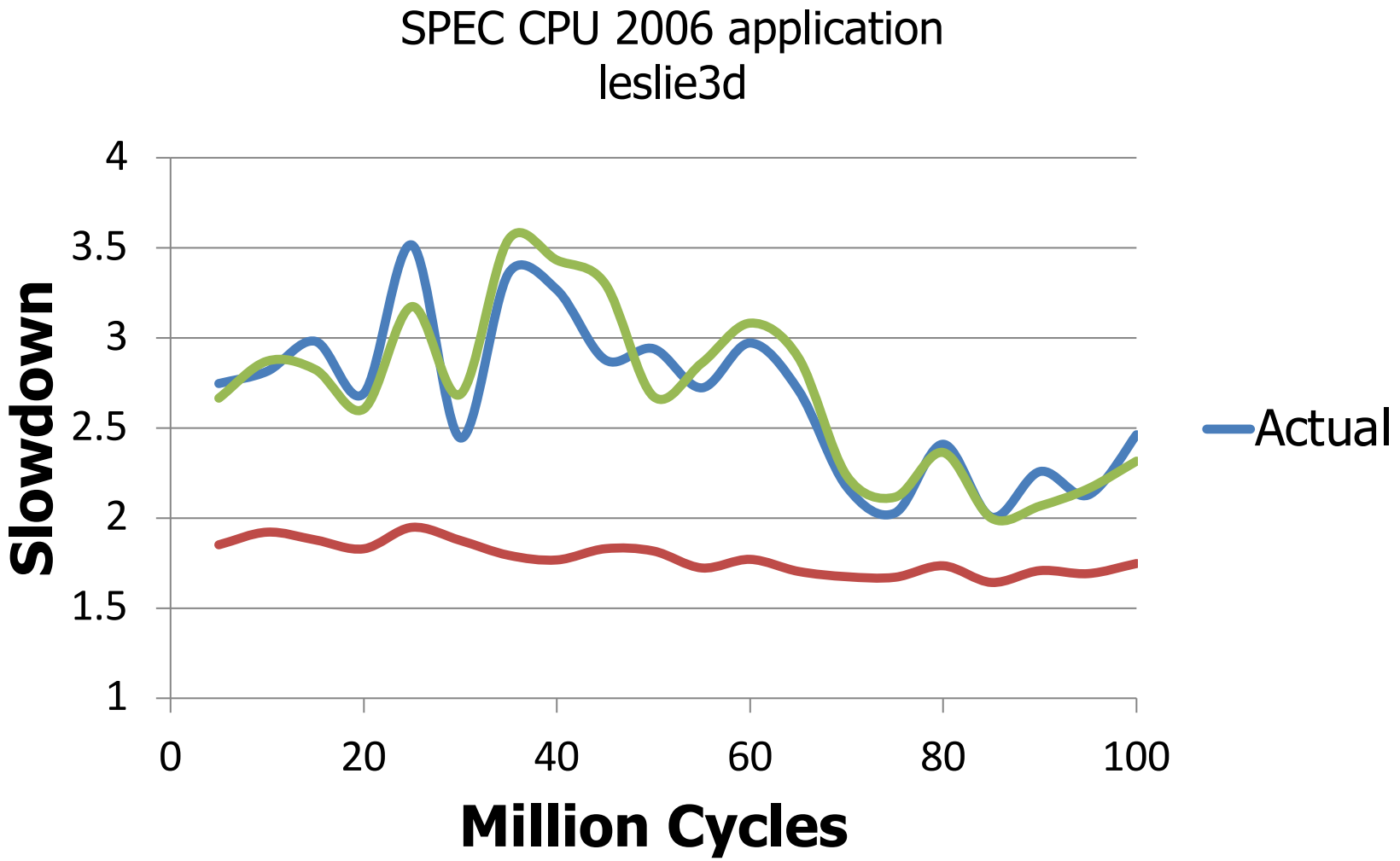
- Advantage 1:
  - STFM estimates alone performance while an application is receiving interference → Hard
  - MISE estimates alone performance while giving an application the highest priority → Easier
- Advantage 2:
  - STFM does not take into account compute phase for non-memory-bound applications
  - MISE accounts for compute phase → Better accuracy

Methodology

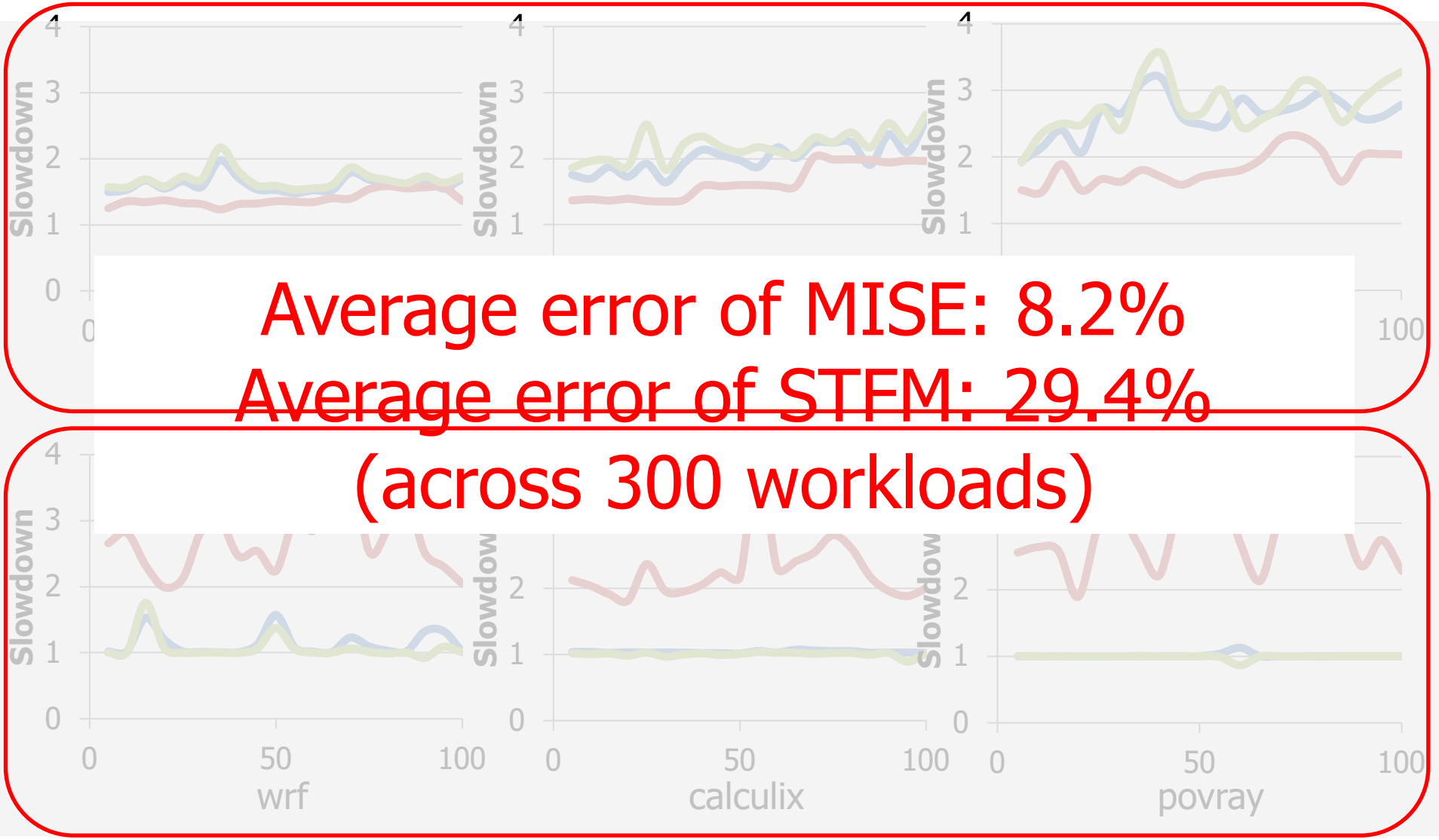
- Configuration of our simulated system
  - 4 cores
  - 1 channel, 8 banks/channel
  - DDR3 1066 DRAM
  - 512 KB private cache/core

- Workloads
  - SPEC CPU2006
  - 300 multi programmed workloads

Quantitative Comparison



Comparison to STFM



Average error of MISE: 8.2%
Average error of STFM: 29.4%
(across 300 workloads)

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Providing "Soft" Slowdown Guarantees

- Goal
  1. Ensure QoS-critical applications meet a prescribed slowdown bound
  2. Maximize system performance for other applications

- Basic Idea
  - Allocate just enough bandwidth to QoS-critical application
  - Assign remaining bandwidth to other applications

MISE-QoS: Mechanism to Provide Soft QoS

- Assign an initial bandwidth allocation to QoS-critical application
- Estimate slowdown of QoS-critical application using the MISE model
- After every N intervals
  - If slowdown > bound B +/- ε, increase bandwidth allocation
  - If slowdown < bound B +/- ε, decrease bandwidth allocation
- When slowdown bound not met for N intervals
  - Notify the OS so it can migrate/de-schedule jobs

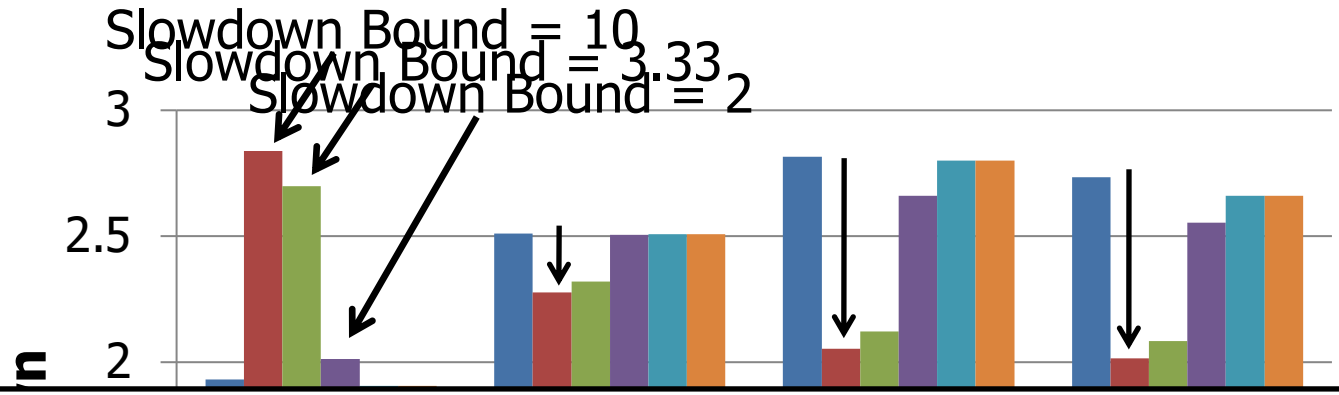
Methodology

- Each application (25 applications in total) considered the QoS-critical application
- Run with 12 sets of co-runners of different memory intensities
- Total of 300 multiprogrammed workloads
- Each workload run with 10 slowdown bound values
- Baseline memory scheduling mechanism
  - Always prioritize QoS-critical application

    [Iyer+, SIGMETRICS 2007]
  - Other applications' requests scheduled in FRFCFS order

    [Zuravleff +, US Patent 1997, Rixner+, ISCA 2000]

A Look at One Workload



MISE is effective in

1. meeting the slowdown bound for the QoS-critical application
2. improving performance of non-QoS-critical applications

leslie3d hmmer lbm omnetpp

QoS-critical **non-QoS-critical**

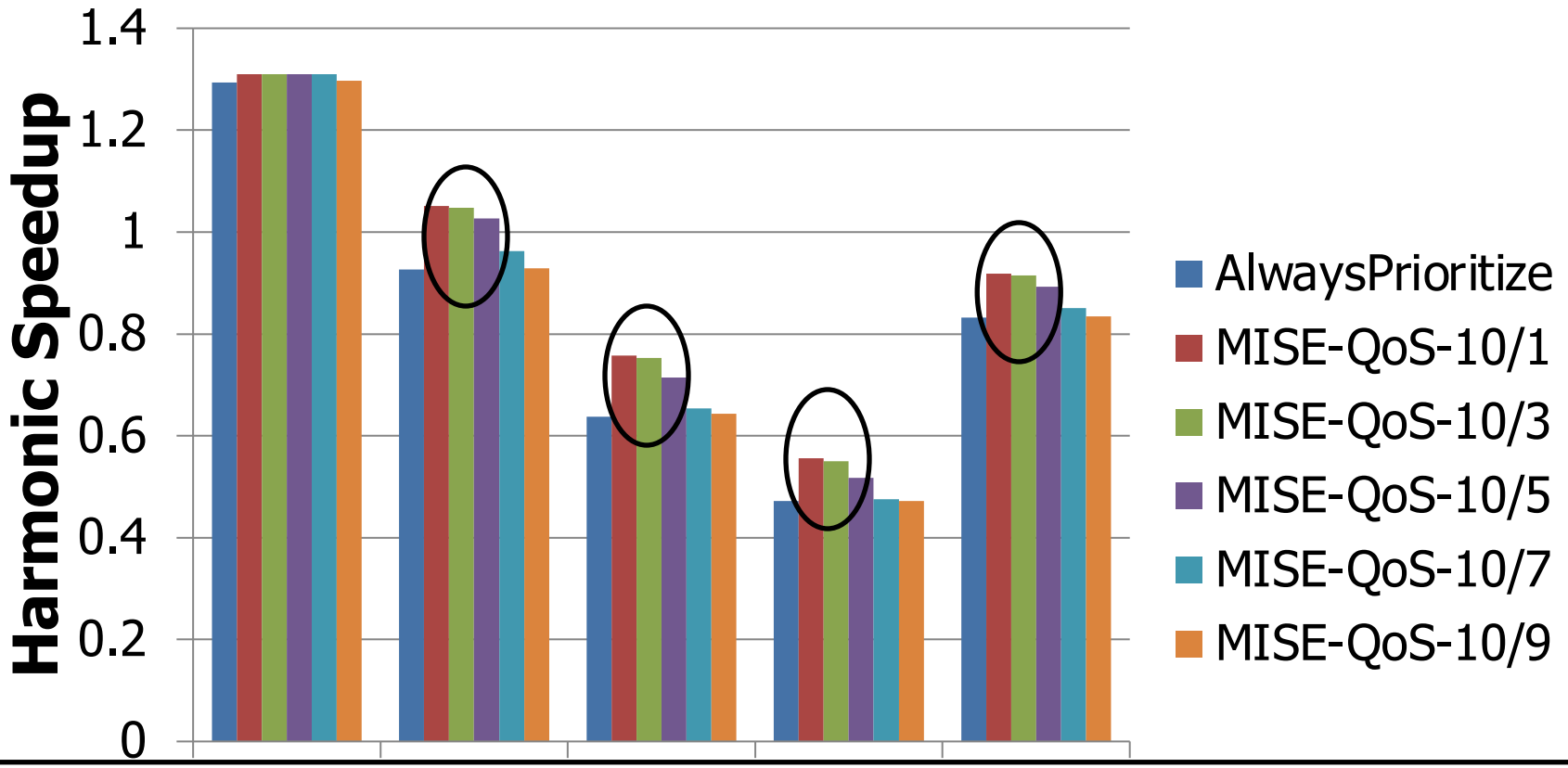
Effectiveness of MISE in Enforcing QoS

Across 3000 data points

	Predicted Met	Predicted Not Met
QoS Bound Met	78.8%	2.1%
QoS Bound Not Met	2.2%	16.9%

MISE-QoS correctly predicts whether or not the bound is met for 95.7% of workloads

Performance of Non-QoS-Critical Applications



When slowdown bound is 10/3
MISE-QoS improves system performance by 10%

Outline

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Other Results in the Paper

- Sensitivity to model parameters
  - Robust across different values of model parameters
- Comparison of STFM and MISE models in enforcing soft slowdown guarantees
  - MISE significantly more effective in enforcing guarantees
- Minimizing maximum slowdown
  - MISE improves fairness across several system configurations

Summary

- Uncontrolled memory interference slows down applications unpredictably
- Goal: Estimate and control slowdowns
- Key contribution
  - MISE: An accurate slowdown estimation model
  - Average error of MISE: 8.2%
- Key Idea
  - Request Service Rate is a proxy for performance
  - Request Service Rate $_{Alone}$ estimated by giving an application highest priority in accessing memory
- Leverage slowdown estimates to control slowdowns
  - Providing soft slowdown guarantees
  - Minimizing maximum slowdown

MISE: Pros and Cons

- Upsides:
  - Simple new insight to estimate slowdown
  - Much more accurate slowdown estimations than prior techniques (STFM, FST)
  - Enables a number of QoS mechanisms that can use slowdown estimates to satisfy performance requirements

- Downsides:
  - Slowdown estimation is not perfect - there are still errors
  - Does not take into account caches and other shared resources in slowdown estimation

More on MISE

- Lavanya Subramanian, Vivek Seshadri, Yoongu Kim, Ben Jaiyen, and Onur Mutlu,
  "MISE: Providing Performance Predictability and Improving Fairness in Shared Main Memory Systems"
  *Proceedings of the 19th International Symposium on High-Performance Computer Architecture (**HPCA**)*, Shenzhen, China, February 2013. Slides (pptx)

MISE: Providing Performance Predictability and Improving Fairness in Shared Main Memory Systems

Lavanya Subramanian Vivek Seshadri Yoongu Kim Ben Jaiyen Onur Mutlu
Carnegie Mellon University

Extending MISE to Shared Caches: ASM

- Lavanya Subramanian, Vivek Seshadri, Arnab Ghosh, Samira Khan, and Onur Mutlu,
  "The Application Slowdown Model: Quantifying and Controlling the Impact of Inter-Application Interference at Shared Caches and Main Memory"
  *Proceedings of the 48th International Symposium on Microarchitecture (**MICRO**)*, Waikiki, Hawaii, USA, December 2015.
  [Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)] [Poster (pptx) (pdf)]
  [Source Code]

The Application Slowdown Model: Quantifying and Controlling the Impact of Inter-Application Interference at Shared Caches and Main Memory

Lavanya Subramanian*§ Vivek Seshadri* Arnab Ghosh*†
Samira Khan*‡ Onur Mutlu*

*Carnegie Mellon University §Intel Labs †IIT Kanpur ‡University of Virginia

Other Ways of Handling Memory Interference

Fundamental Interference Control Techniques

- Goal: to reduce/control inter-thread memory interference

1. Prioritization or request scheduling

2. Data mapping to banks/channels/ranks

3. Core/source throttling

4. Application/thread scheduling

Designing QoS-Aware Memory Systems: Approaches

- Smart resources: Design each shared resource to have a configurable interference control/reduction mechanism
  - QoS-aware memory controllers
  - QoS-aware interconnects
  - QoS-aware caches

- Dumb resources: Keep each resource free-for-all, but reduce/control interference by injection control or data mapping
  - Source throttling to control access to memory system
  - QoS-aware data mapping to memory controllers
  - QoS-aware thread scheduling to cores

Fundamental Interference Control Techniques

- Goal: to reduce/control inter-thread memory interference

1. Prioritization or request scheduling

2. Data mapping to banks/channels/ranks

3. Core/source throttling

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More on Source Throttling (I)

Eiman Ebrahimi, Chang Joo Lee, Onur Mutlu, and Yale N. Patt,
"Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems"
*Proceedings of the 15th International Conference on Architectural Support for Programming Languages and Operating Systems (**ASPLOS**)*, pages 335-346, Pittsburgh, PA, March 2010. Slides (pdf)
Best paper award.

Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems

Eiman Ebrahimi† Chang Joo Lee† Onur Mutlu§ Yale N. Patt†

†Department of Electrical and Computer Engineering
The University of Texas at Austin
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§Computer Architecture Laboratory (CALCM)
Carnegie Mellon University
onur@cmu.edu

More on Source Throttling (II)

- Kevin Chang, Rachata Ausavarungnirun, Chris Fallin, and Onur Mutlu, **"HAT: Heterogeneous Adaptive Throttling for On-Chip Networks"**
  *Proceedings of the 24th International Symposium on Computer Architecture and High Performance Computing (**SBAC-PAD**)*, New York, NY, October 2012. Slides (pptx) (pdf)

HAT: Heterogeneous Adaptive Throttling for On-Chip Networks

Kevin Kai-Wei Chang, Rachata Ausavarungnirun, Chris Fallin, Onur Mutlu
Carnegie Mellon University
{kevincha,rachata,cfallin,onur}@cmu.edu

More on Source Throttling (III)

- George Nychis, Chris Fallin, Thomas Moscibroda, Onur Mutlu, and Srinivasan Seshan,
  "On-Chip Networks from a Networking Perspective: Congestion and Scalability in Many-core Interconnects"
  *Proceedings of the 2012 ACM SIGCOMM Conference (**SIGCOMM**)*, Helsinki, Finland, August 2012. Slides (pptx)

On-Chip Networks from a Networking Perspective: Congestion and Scalability in Many-Core Interconnects

George Nychis†, Chris Fallin†, Thomas Moscibroda§, Onur Mutlu†, Srinivasan Seshan†

† Carnegie Mellon University
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Fundamental Interference Control Techniques

- Goal: to reduce/control interference

1. Prioritization or request scheduling

2. Data mapping to banks/channels/ranks

3. Core/source throttling

4. Application/thread scheduling

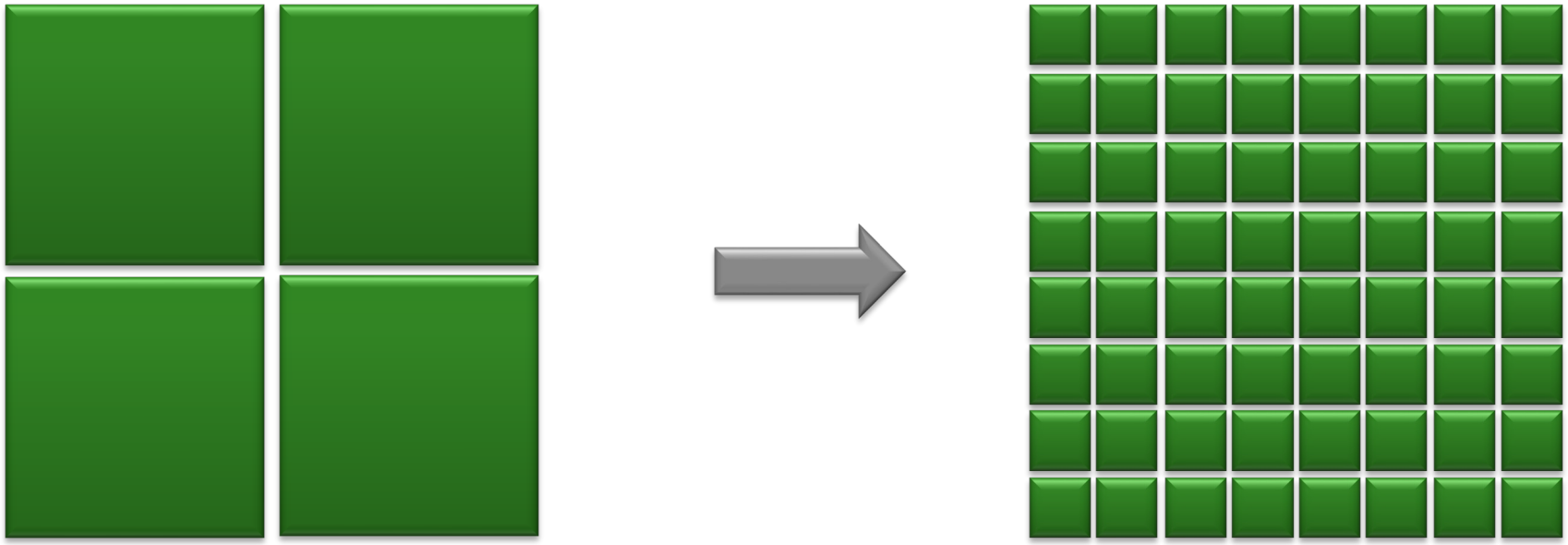
Idea: Pick threads that do not badly interfere with each other to be scheduled together on cores sharing the memory system

Application-to-Core Mapping to Reduce Interference

- Reetuparna Das, Rachata Ausavarungnirun, Onur Mutlu, Akhilesh Kumar, and Mani Azimi,
  "Application-to-Core Mapping Policies to Reduce Memory System Interference in Multi-Core Systems"
  *Proceedings of the 19th International Symposium on High-Performance Computer Architecture (**HPCA**)*, Shenzhen, China, February 2013.
  Slides (pptx)

- Key ideas:
  - Cluster threads to memory controllers (to reduce across chip interference)
  - Isolate interference-sensitive (low-intensity) applications in a separate cluster (to reduce interference from high-intensity applications)
  - Place applications that benefit from memory bandwidth closer to the controller

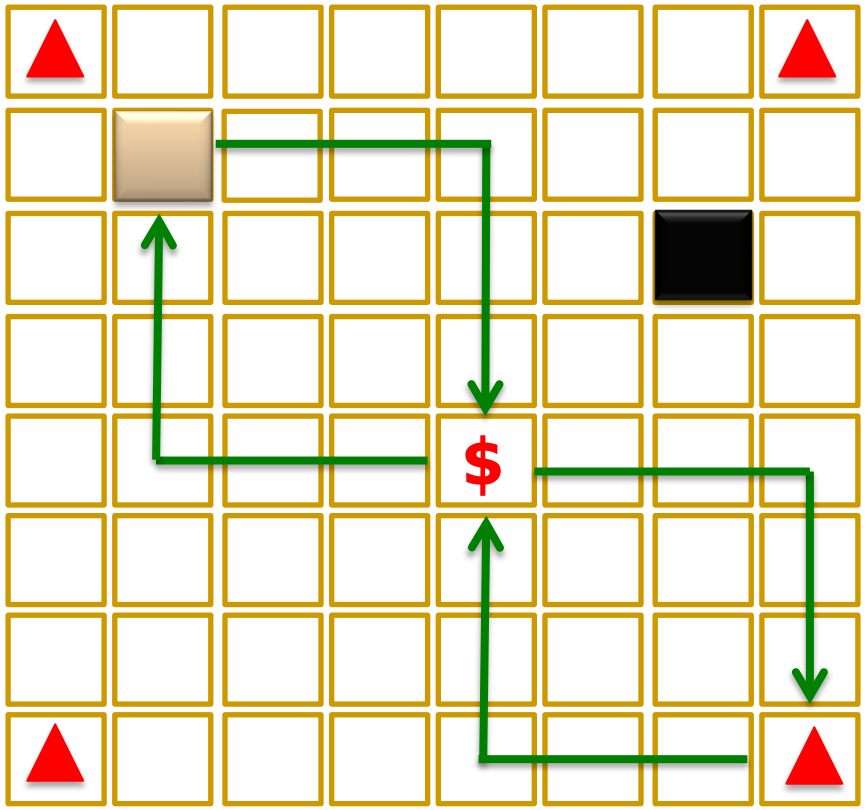
Multi-Core to Many-Core

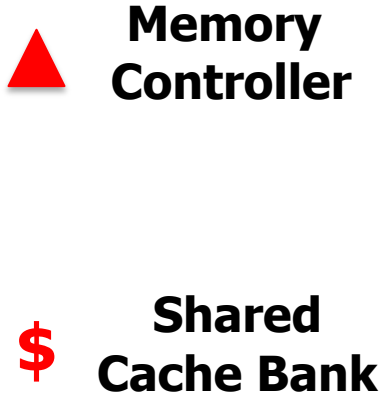


Multi-Core **Many-Core**

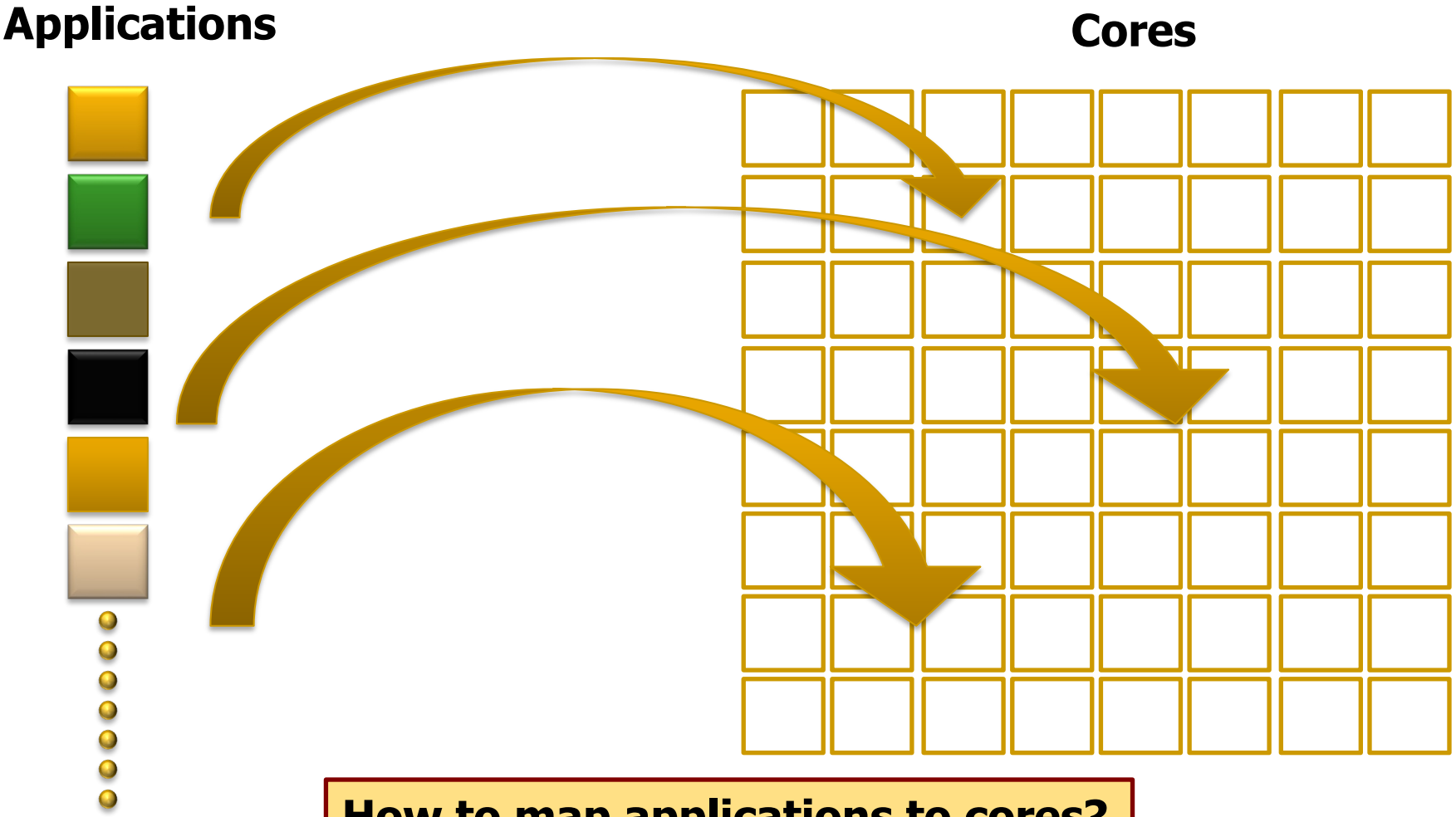
Many-Core On-Chip Communication

Applications



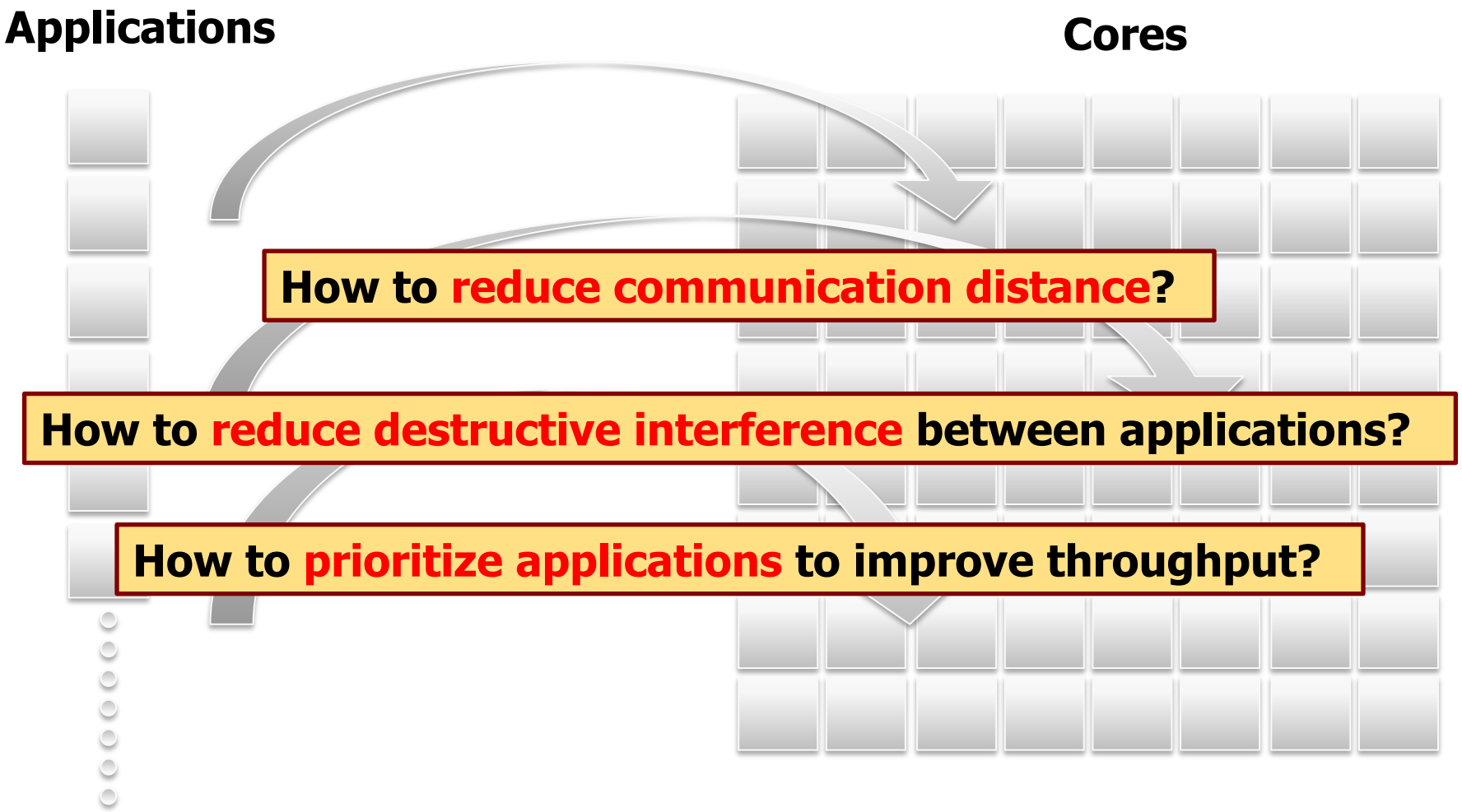


Problem: Spatial Task Scheduling

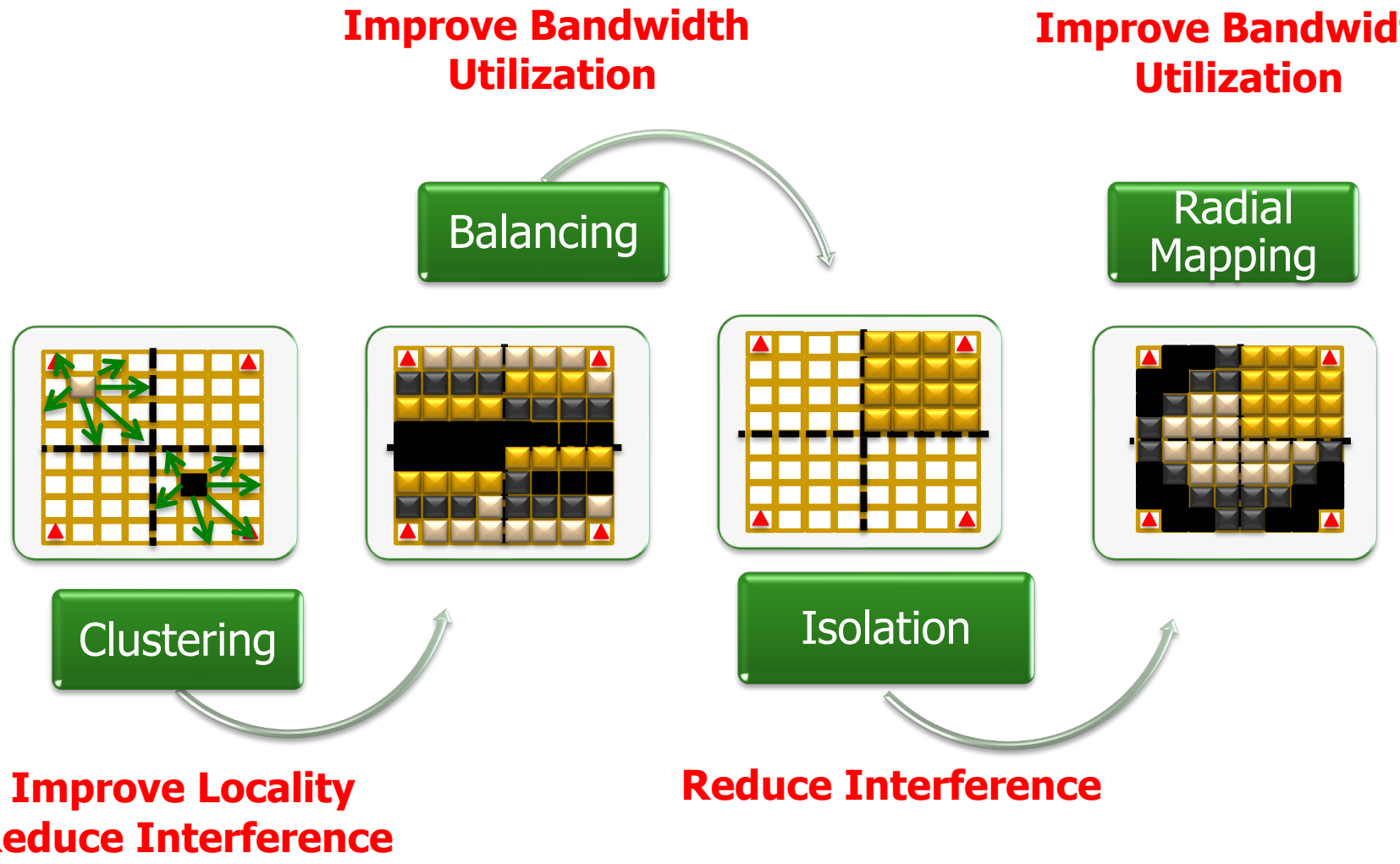


How to map applications to cores?

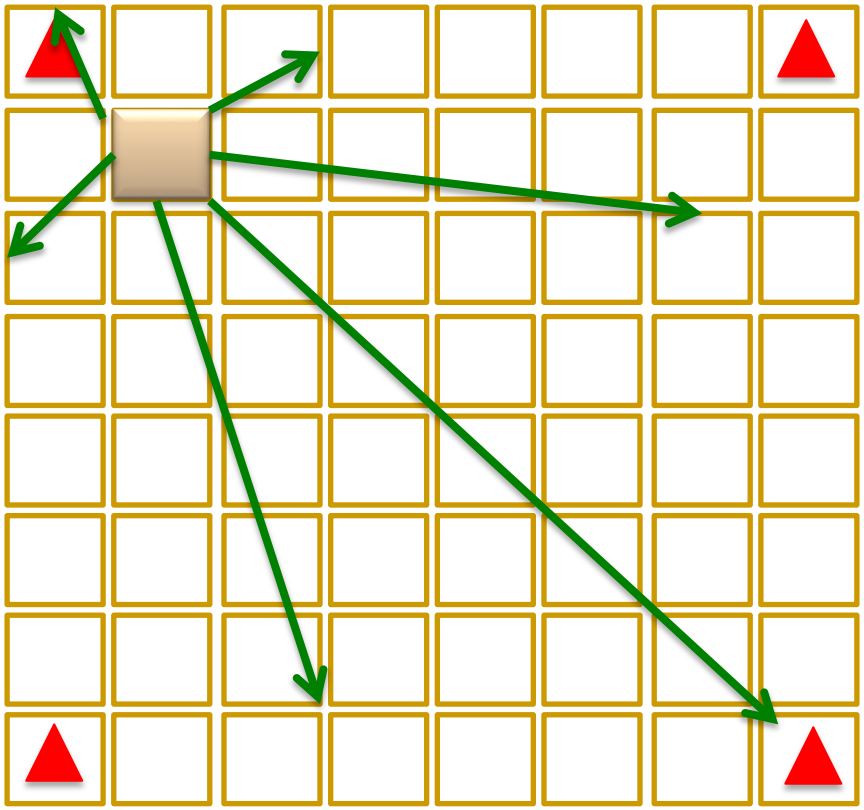
Challenges in Spatial Task Scheduling



Application-to-Core Mapping



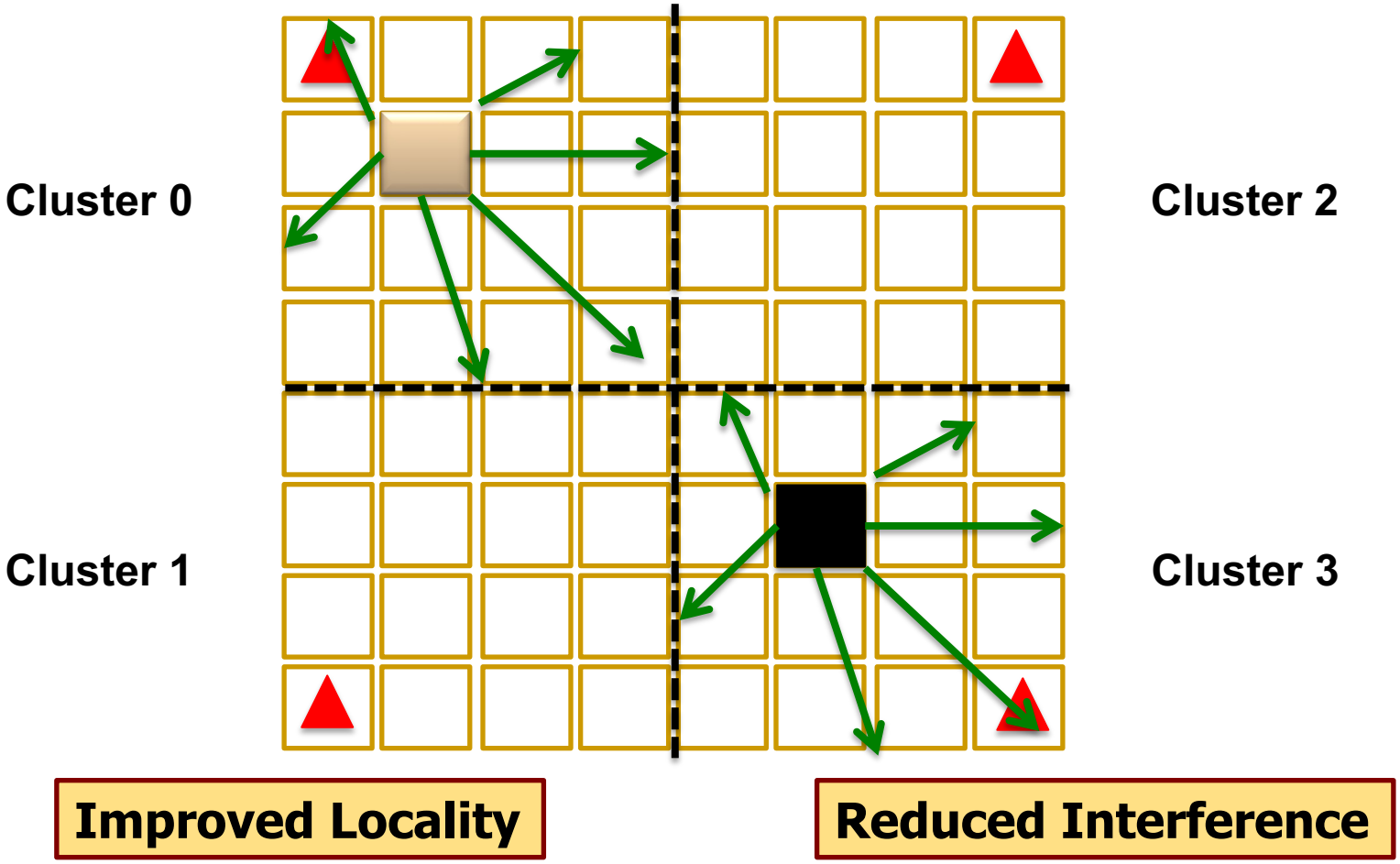
Step 1 — Clustering



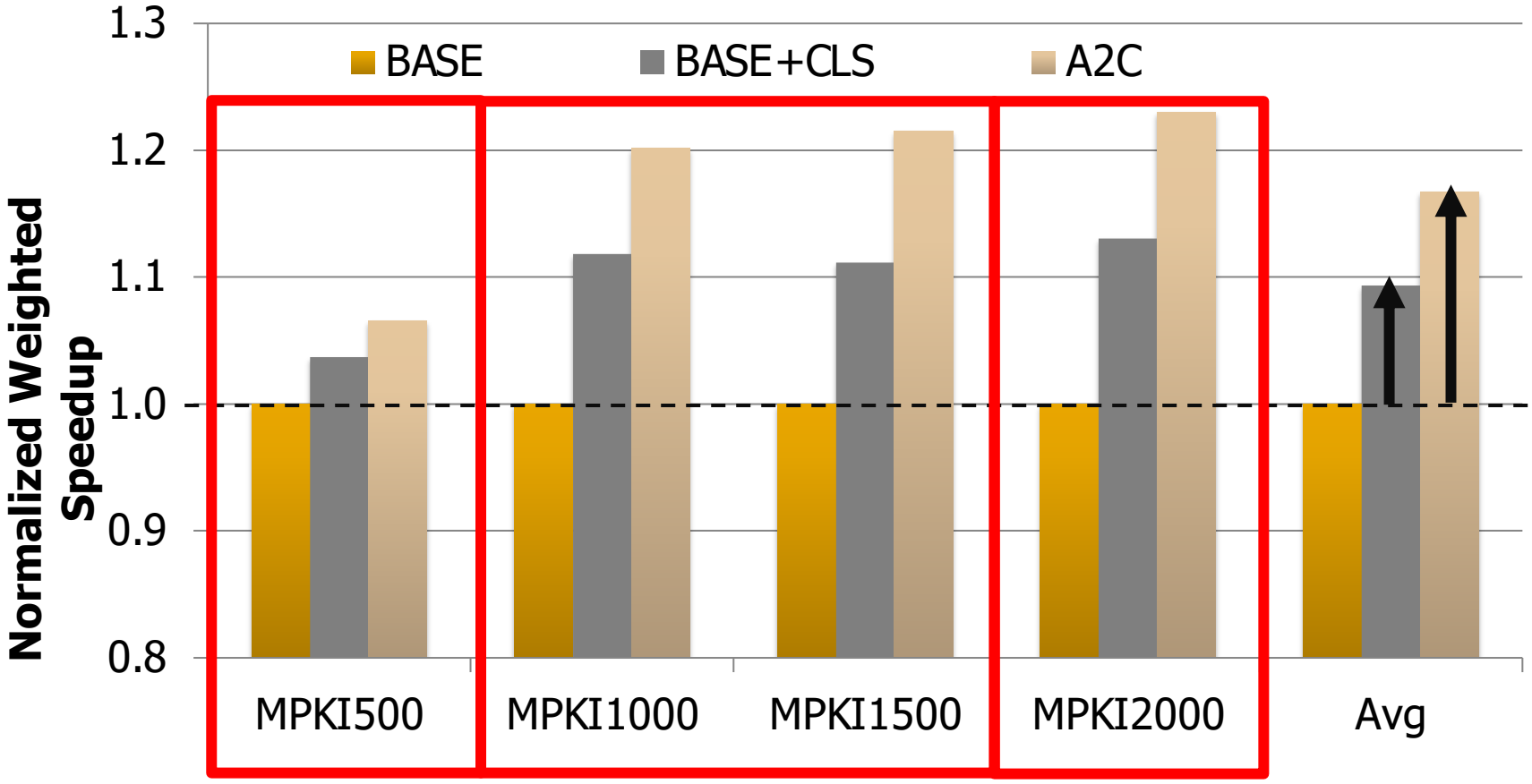
Memory Controller

Inefficient data mapping to memory and caches

Step 1 — Clustering

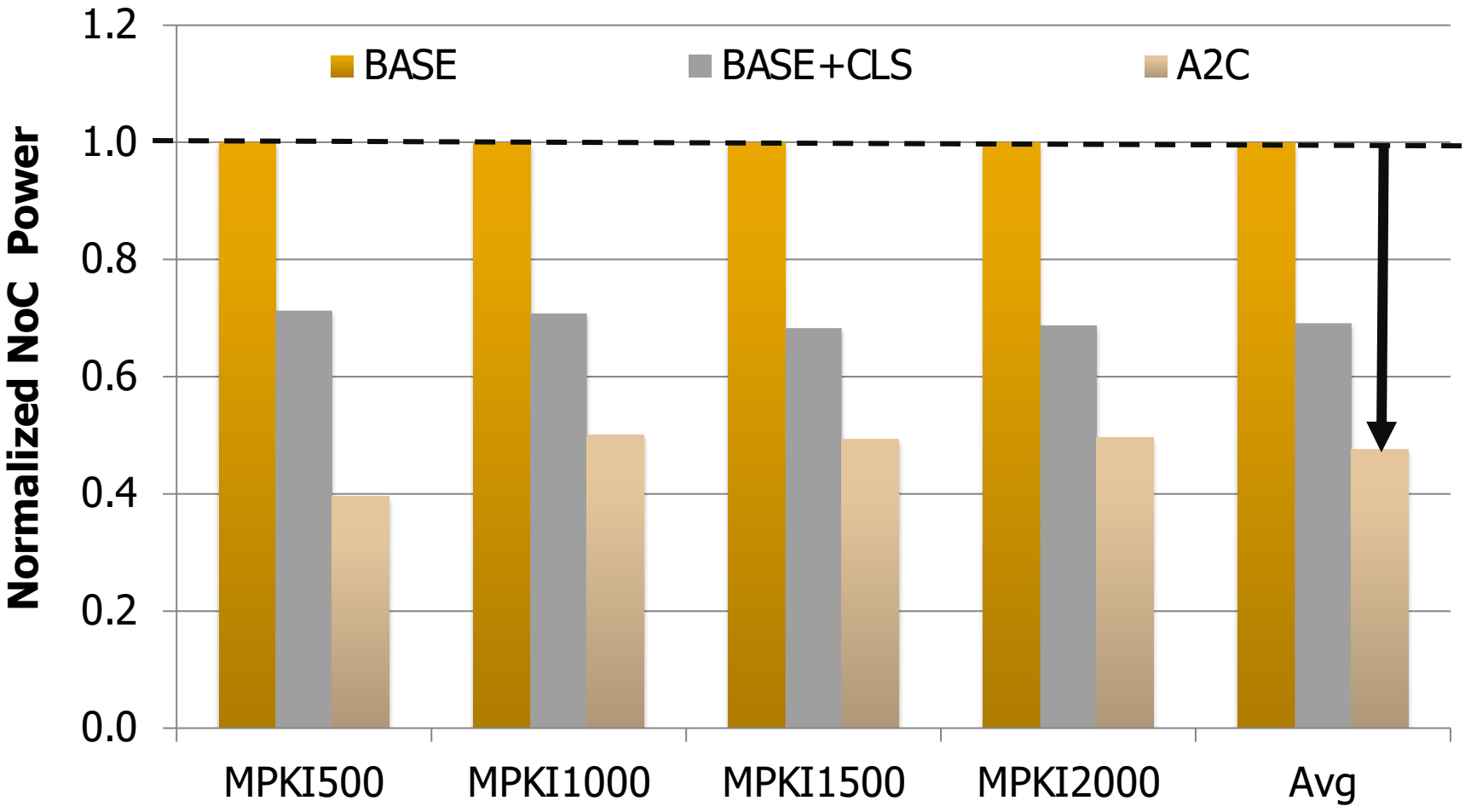


System Performance



System performance improves by 17%

Network Power



Average network power consumption reduces by 52%

More on App-to-Core Mapping

- Reetuparna Das, Rachata Ausavarungnirun, Onur Mutlu, Akhilesh Kumar, and Mani Azimi,
  "Application-to-Core Mapping Policies to Reduce Memory System Interference in Multi-Core Systems"
  *Proceedings of the 19th International Symposium on High-Performance Computer Architecture (**HPCA**)*, Shenzhen, China, February 2013.
  Slides (pptx)

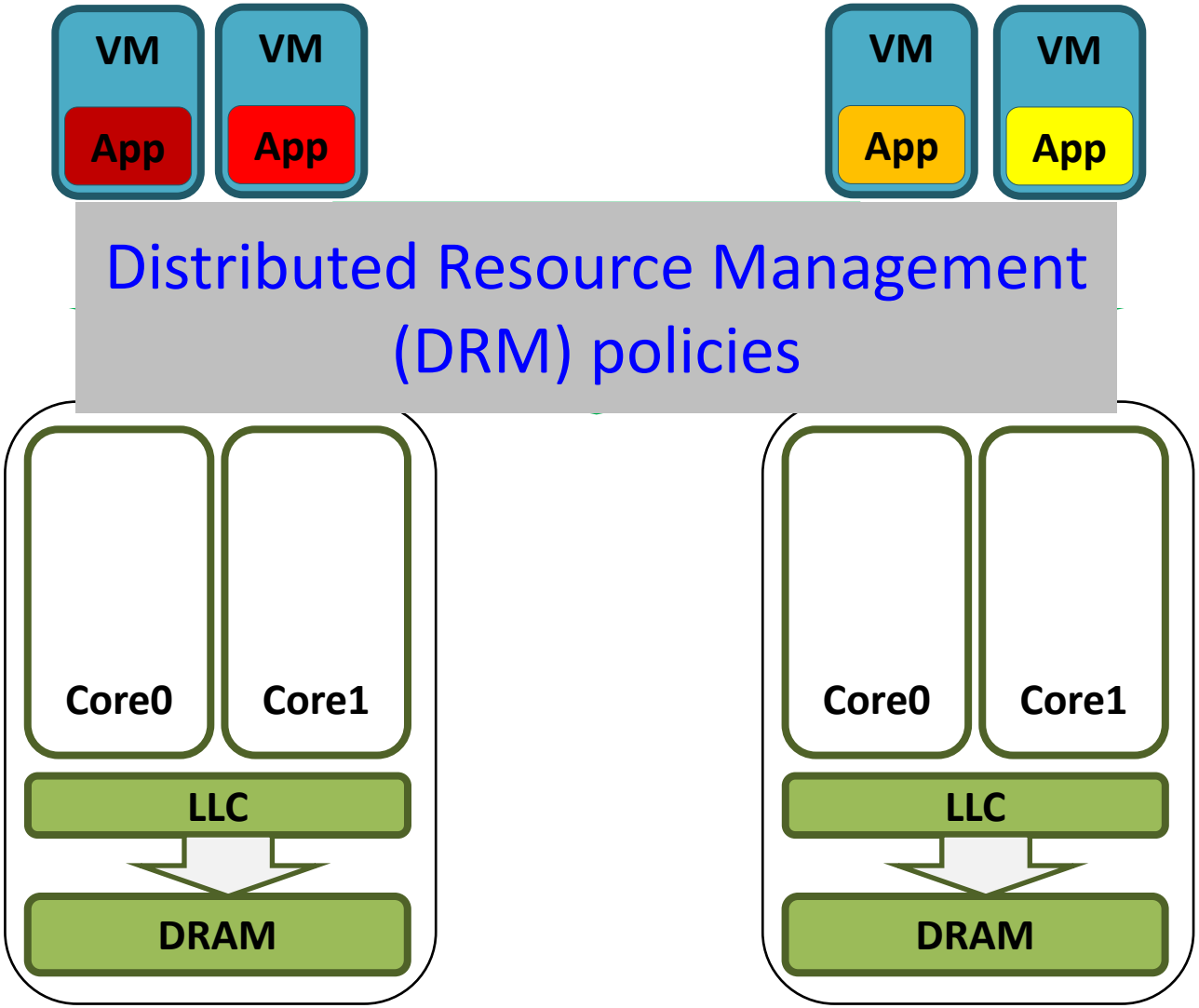
Application-to-Core Mapping Policies to Reduce Memory System Interference in Multi-Core Systems

Reetuparna Das* Rachata Ausavarungnirun† Onur Mutlu† Akhilesh Kumar‡ Mani Azimi‡
University of Michigan* Carnegie Mellon University† Intel Labs‡

Interference-Aware Thread Scheduling

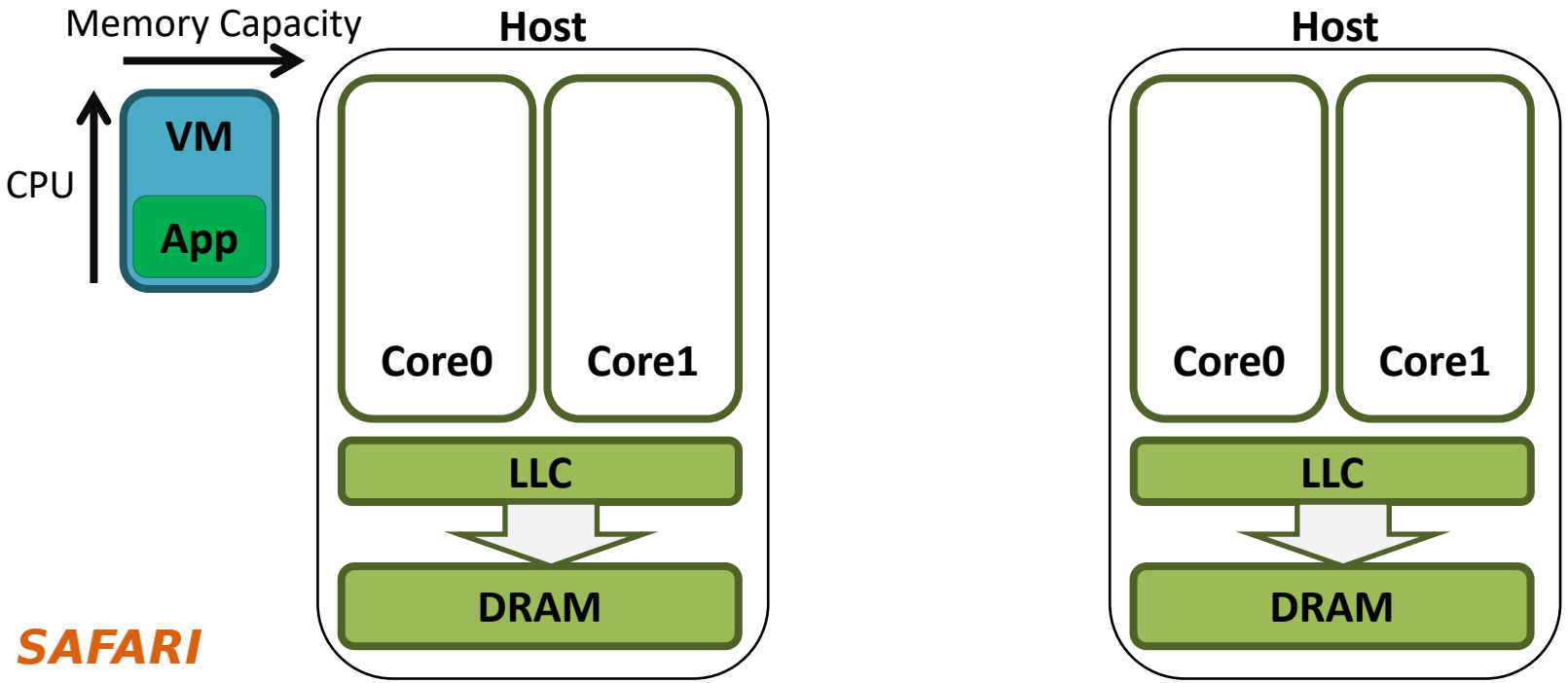
- An example from scheduling in compute clusters (data centers)
- Data centers can be running virtual machines

Virtualized Cluster



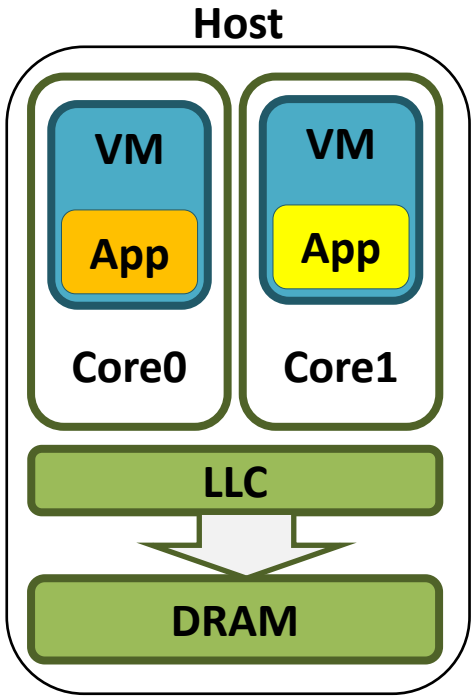
Conventional DRM Policies

Based on operating-system-level metrics
e.g., CPU utilization, memory capacity demand



Microarchitecture-level Interference

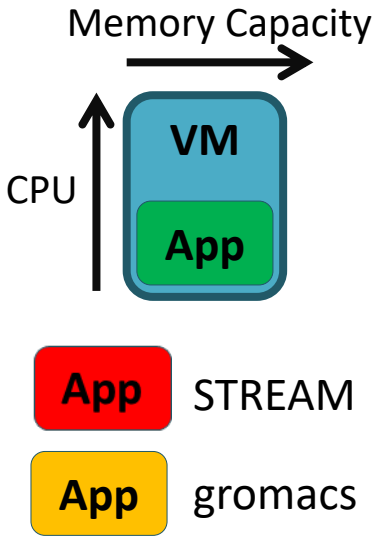
- VMs within a host compete for:
  - Shared cache capacity
  - Shared memory bandwidth

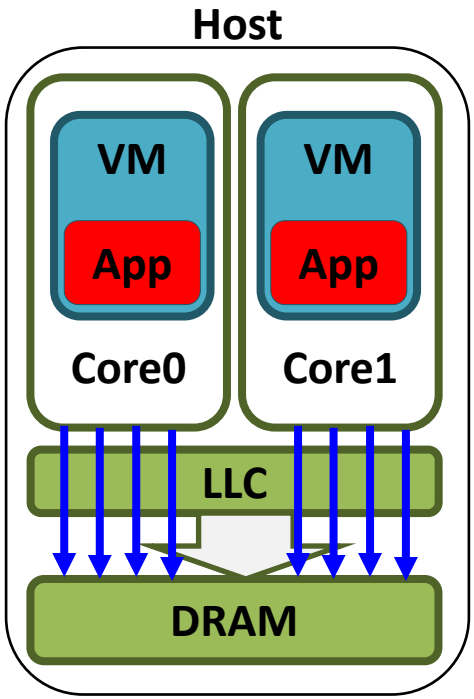


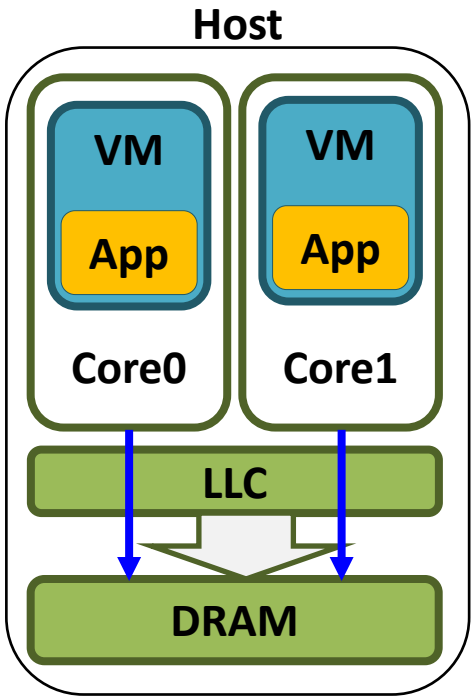
Can operating-system-level metrics capture the microarchitecture-level resource interference?

Microarchitecture Unawareness

VM	Operating-system-level metrics		Microarchitecture-level metrics	
	CPU Utilization	Memory Capacity	LLC Hit Ratio	Memory Bandwidth
App	92%	369 MB	2%	2267 MB/s
App	93%	348 MB	98%	1 MB/s

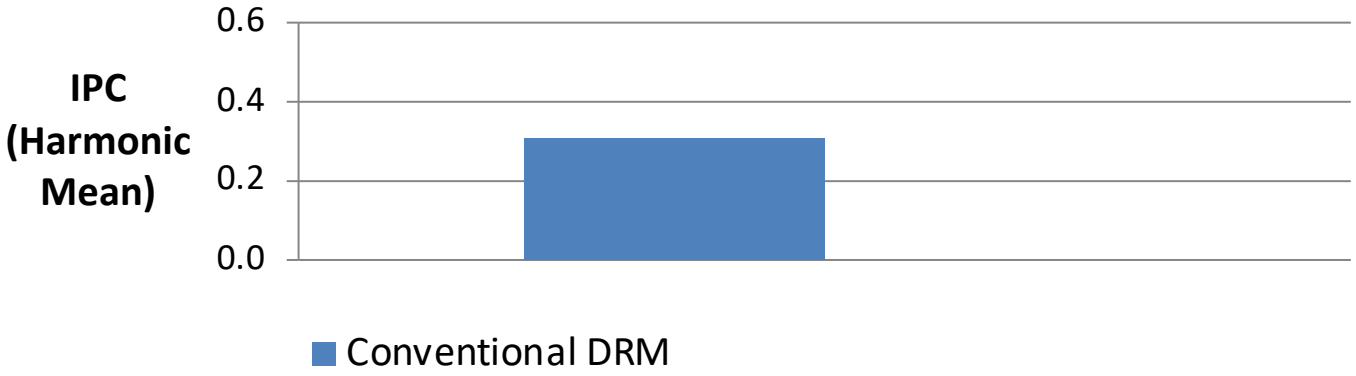


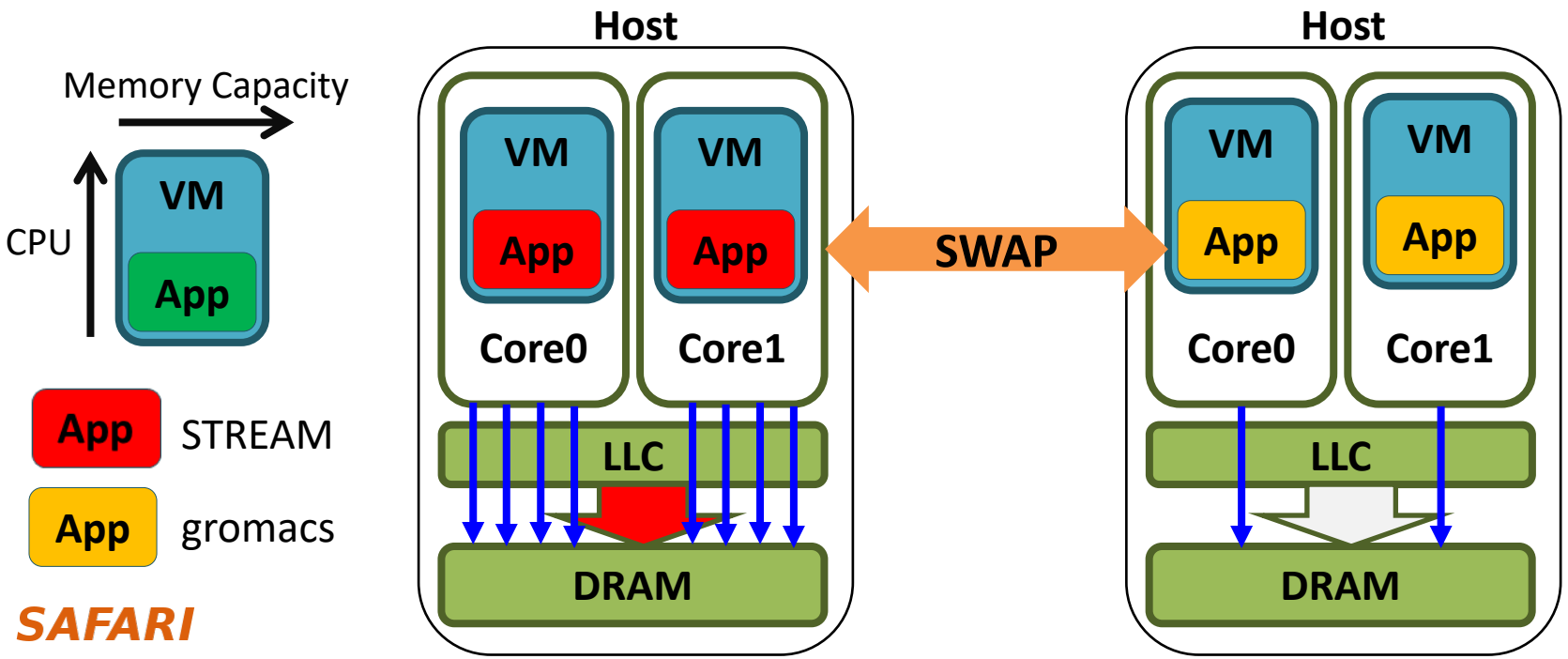




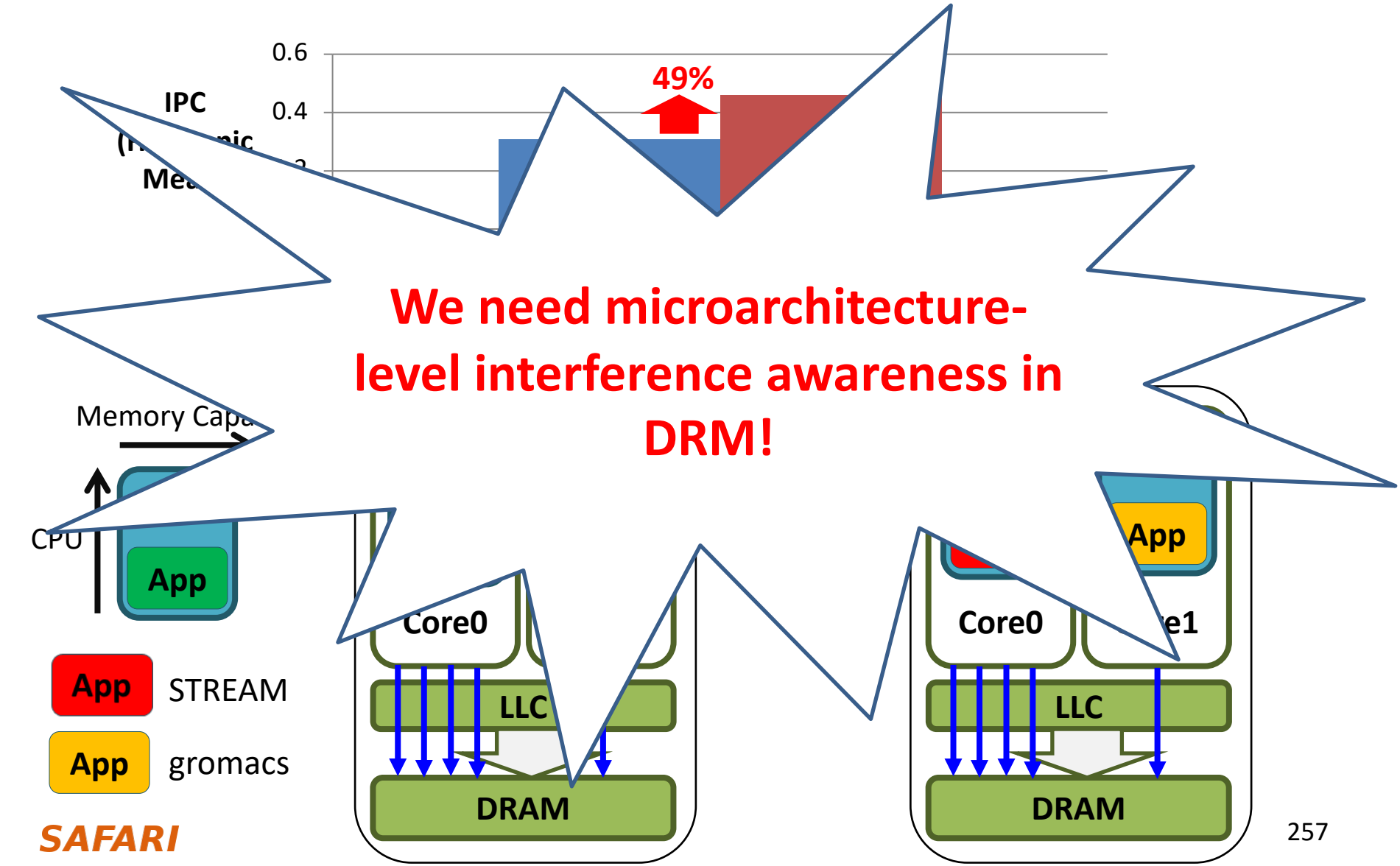
SAFARI

Impact on Performance





Impact on Performance

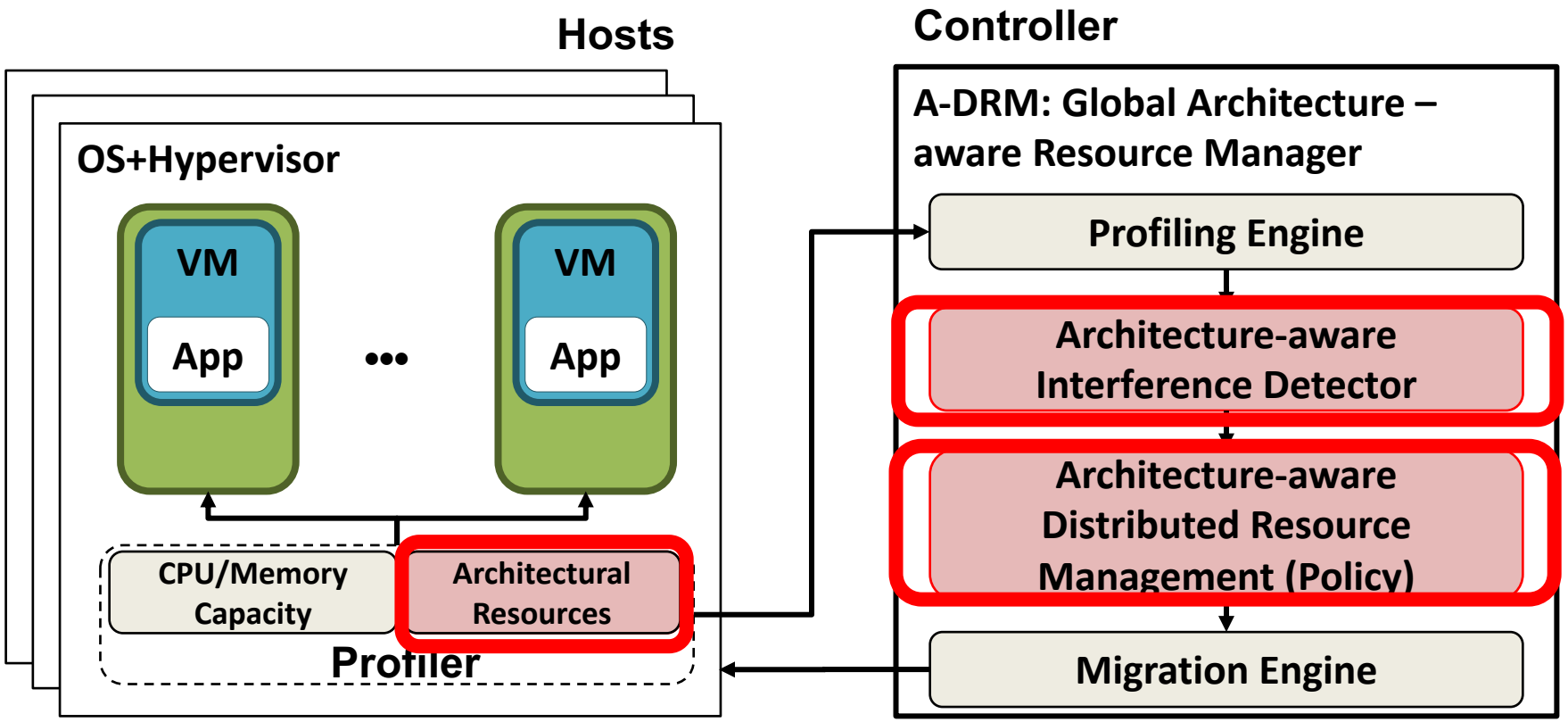


A-DRM: Architecture-aware DRM

- **Goal**: Take into account microarchitecture-level shared resource interference
  - Shared cache capacity
  - Shared memory bandwidth

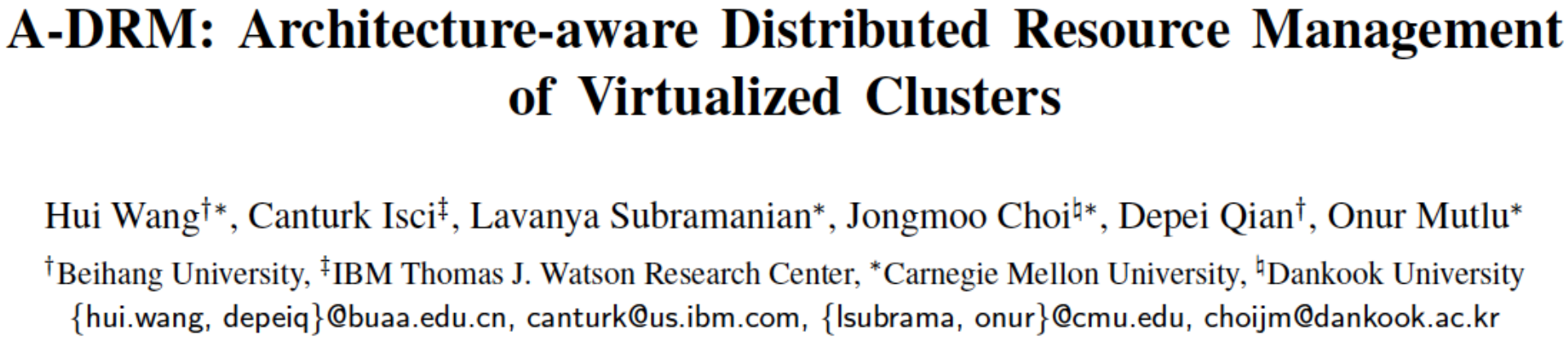
- **Key Idea**:
  - Monitor and detect microarchitecture-level shared resource interference
  - Balance microarchitecture-level resource usage across cluster to minimize memory interference while maximizing system performance

A-DRM: Architecture-aware DRM



More on Architecture-Aware DRM

- Hui Wang, Canturk Isci, Lavanya Subramanian, Jongmoo Choi, Depei Qian, and Onur Mutlu,
  "A-DRM: Architecture-aware Distributed Resource Management of Virtualized Clusters"
  *Proceedings of the 11th ACM SIGPLAN/SIGOPS International Conference on Virtual Execution Environments (**VEE**)*, Istanbul, Turkey, March 2015.
  [Slides (pptx) (pdf)]



A-DRM: Architecture-aware Distributed Resource Management of Virtualized Clusters

Hui Wang[†*], Canturk Isci[‡], Lavanya Subramanian[*], Jongmoo Choi[♮*], Depei Qian[†], Onur Mutlu[*]
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Interference-Aware Thread Scheduling

- Advantages

  + Can eliminate/minimize interference by scheduling "symbiotic applications" together (as opposed to just managing the interference)

  + Less intrusive to hardware (less need to modify the hardware resources)

- Disadvantages and Limitations

  -- High overhead to migrate threads and data between cores and machines

  -- Does not work (well) if all threads are similar and they interfere

Summary

Summary: Fundamental Interference Control Techniques

- Goal: to reduce/control interference

1. Prioritization or request scheduling

2. Data mapping to banks/channels/ranks

3. Core/source throttling

4. Application/thread scheduling

Best is to combine all. How would you do that?

Summary: Memory QoS Approaches and Techniques

- Approaches: Smart vs. dumb resources
  - Smart resources: QoS-aware memory scheduling
  - Dumb resources: Source throttling; channel partitioning
  - Both approaches are effective at reducing interference
  - No single best approach for all workloads
- Techniques: Request/thread scheduling, source throttling, memory partitioning
  - All approaches are effective at reducing interference
  - Can be applied at different levels: hardware vs. software
  - No single best technique for all workloads
- Combined approaches and techniques are the most powerful
  - Integrated Memory Channel Partitioning and Scheduling [MICRO'11]

Summary: Memory Interference and QoS

- QoS-unaware memory → uncontrollable and unpredictable system
- Providing QoS awareness improves performance, predictability, fairness, and utilization of the memory system
- Discussed many new techniques to:
  - Minimize memory interference
  - Provide predictable performance
- Many new research ideas needed for integrated techniques and closing the interaction with software

What Did We Not Cover?

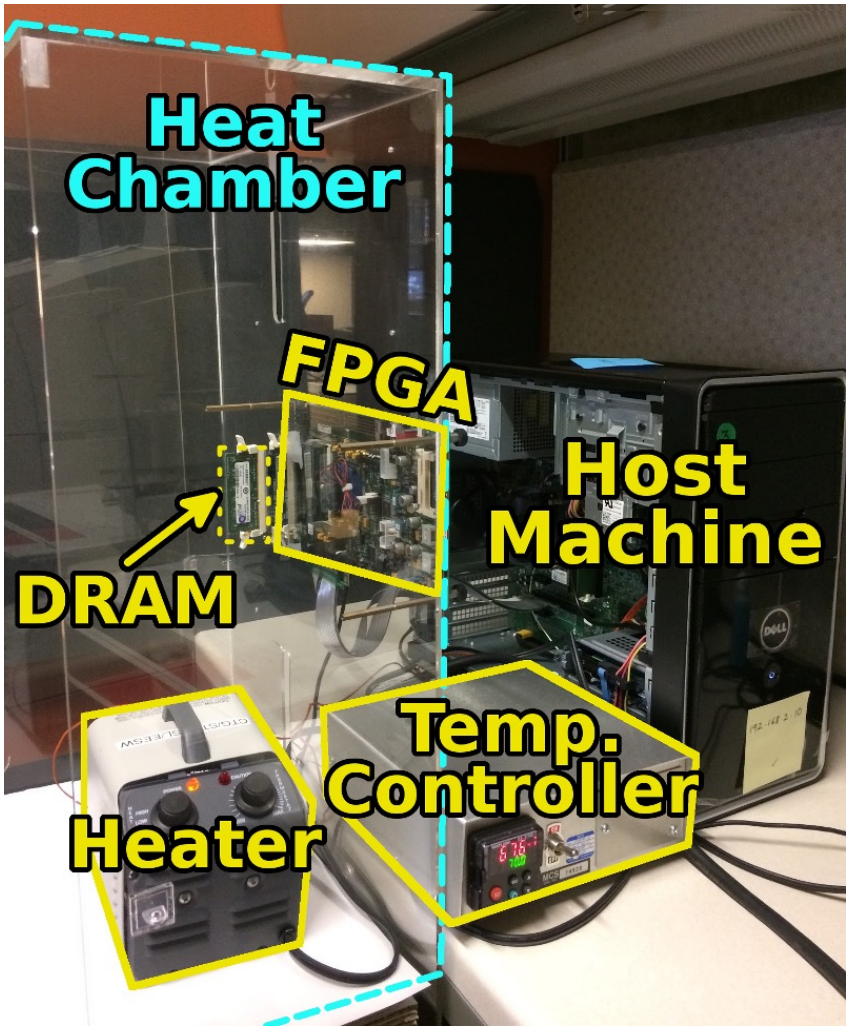
- Prefetch-aware shared resource management
- DRAM-controller co-design
- Cache interference management
- **Interconnect interference management**
- Write-read scheduling
- **DRAM designs to reduce interference**
- Interference issues in near-memory processing
- …

What the Future May Bring

- Memory QoS techniques for heterogeneous SoC systems
  - Many accelerators, processing in/near memory, better predictability, higher performance
- Combinations of memory QoS/performance techniques
  - E.g., data mapping and scheduling
- Fundamentally more intelligent designs that use **machine learning**
- Real prototypes

SoftMC: Open Source DRAM Infrastructure

- Hasan Hassan et al., **"SoftMC: A Flexible and Practical Open-Source Infrastructure for Enabling Experimental DRAM Studies,"** HPCA 2017.



- **Flexible**
- **Easy to Use (C++ API)**
- **Open-source**

  github.com/CMU-SAFARI/SoftMC

SoftMC

- **https://github.com/CMU-SAFARI/SoftMC**

SoftMC: A Flexible and Practical Open-Source Infrastructure for Enabling Experimental DRAM Studies

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Gennady Pekhimenko[5,3] Donghyuk Lee[6,3] Oguz Ergin[2] Onur Mutlu[1,3]

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[4]*University of Virginia* [5]*Microsoft Research* [6]*NVIDIA Research*