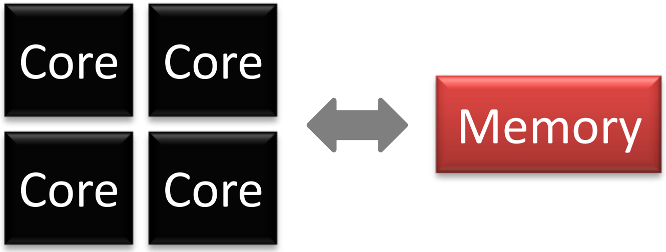
# Thread Cluster Memory Scheduling:
## Exploiting Differences in Memory Access Behavior

**Yoongu Kim**
Michael Papamichael
Onur Mutlu
Mor Harchol-Balter

Carnegie Mellon

# Motivation

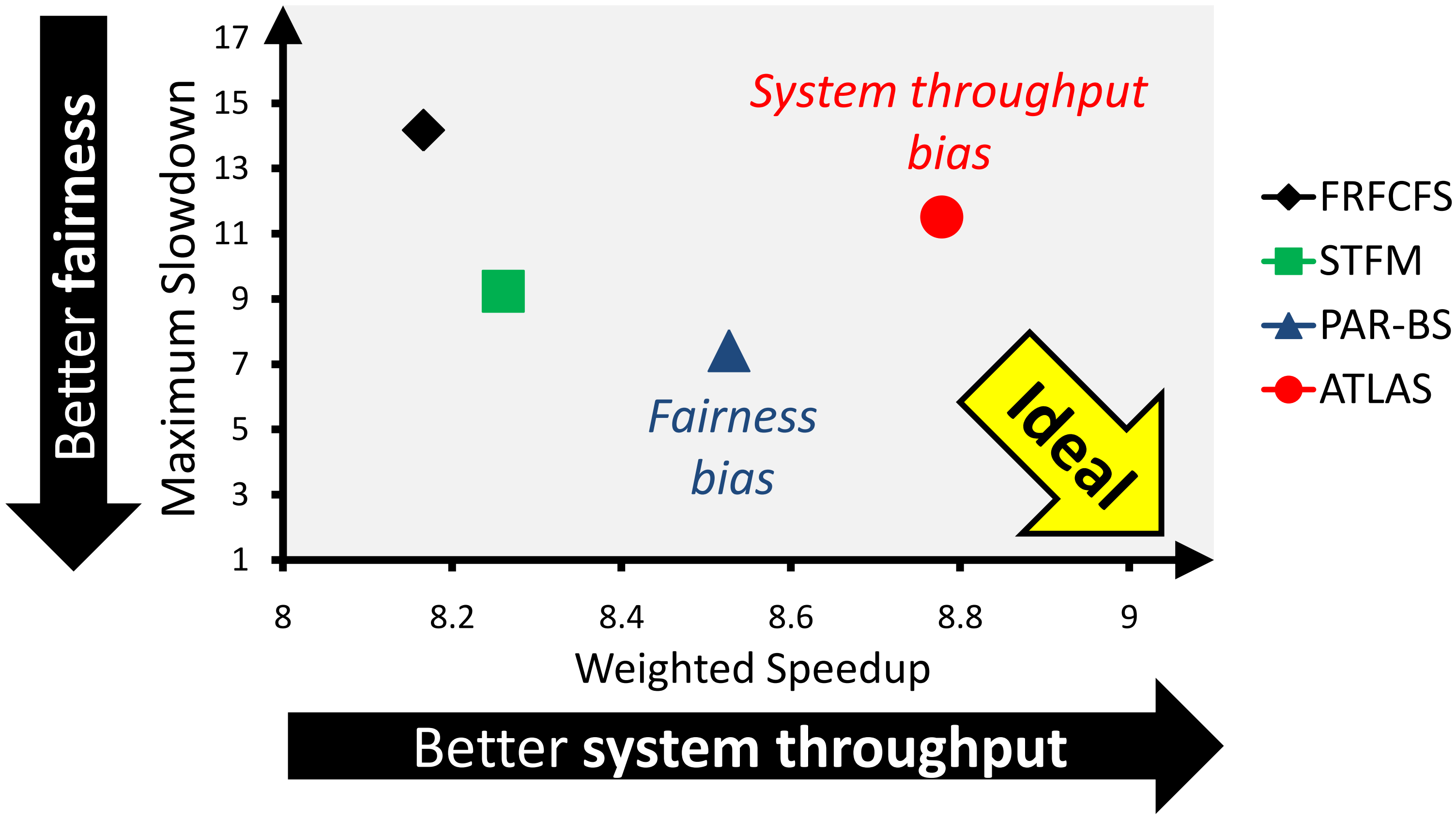
- Memory is a shared resource




- Threads' requests contend for memory
  - Degradation in single thread performance
  - Can even lead to starvation

- How to schedule memory requests to increase both system throughput and fairness?

# Previous Scheduling Algorithms are Biased




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

# Why do Previous Algorithms Fail?

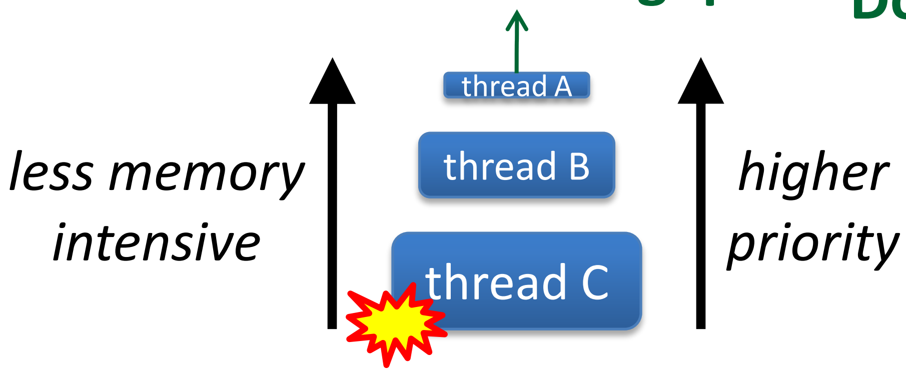
***Throughput biased** approach*

Prioritize less memory-intensive threads

***Fairness biased** approach*

Take turns accessing memory

**Good for throughput**



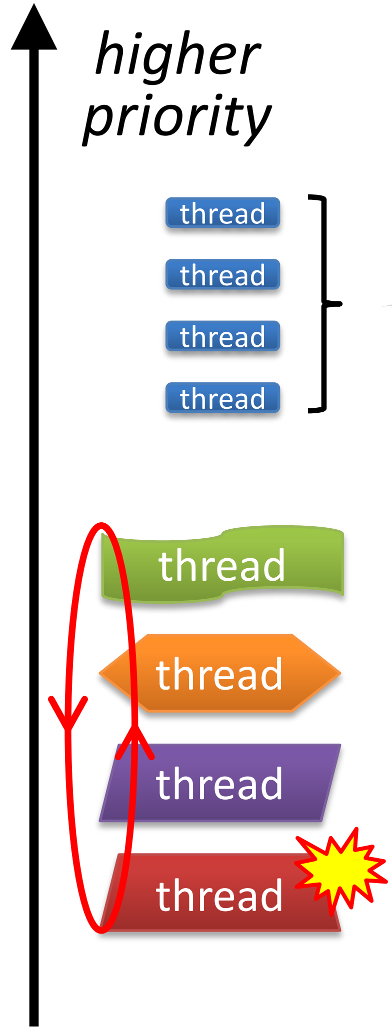

***starvation → unfairness***

**Does not starve**


***not prioritized → reduced throughput***

**Single policy for all threads is insufficient**

# Insight: Achieving Best of Both Worlds




**For Throughput**

**Prioritize memory-non-intensive threads**

**For Fairness**

**Unfairness caused by memory-intensive being prioritized over each other**

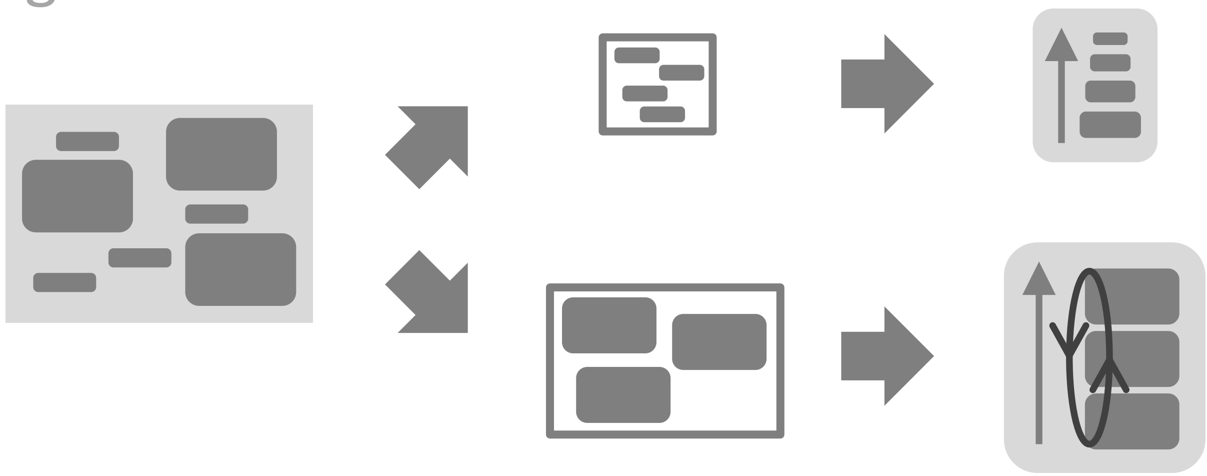
- Shuffle threads

**Memory-intensive threads have different vulnerability to interference**

- Shuffle asymmetrically

# Outline

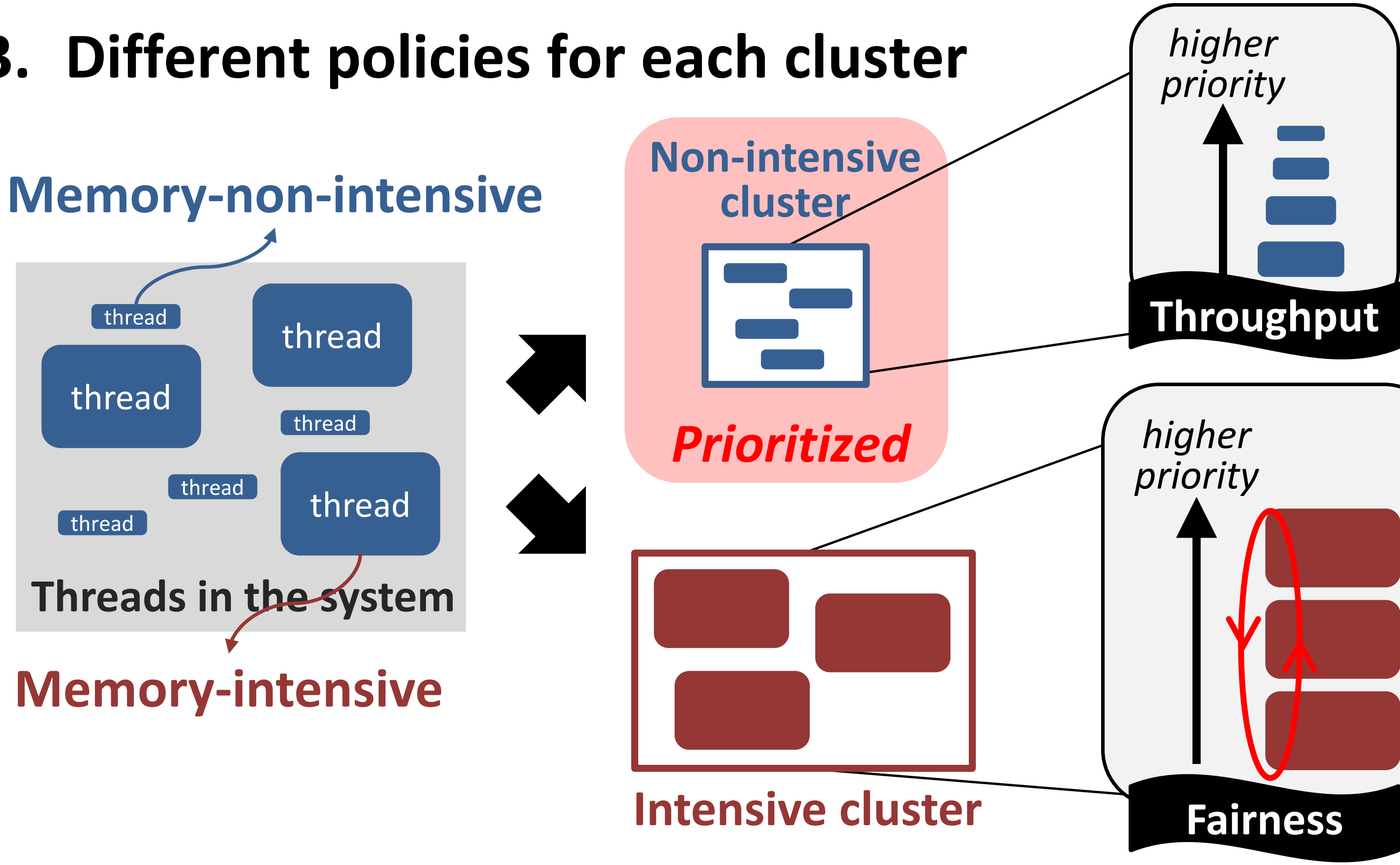
- ❑ Motivation & Insights
- ❑ **Overview**
- ❑ Algorithm



- ❑ Bringing it All Together
- ❑ Evaluation
- ❑ Conclusion

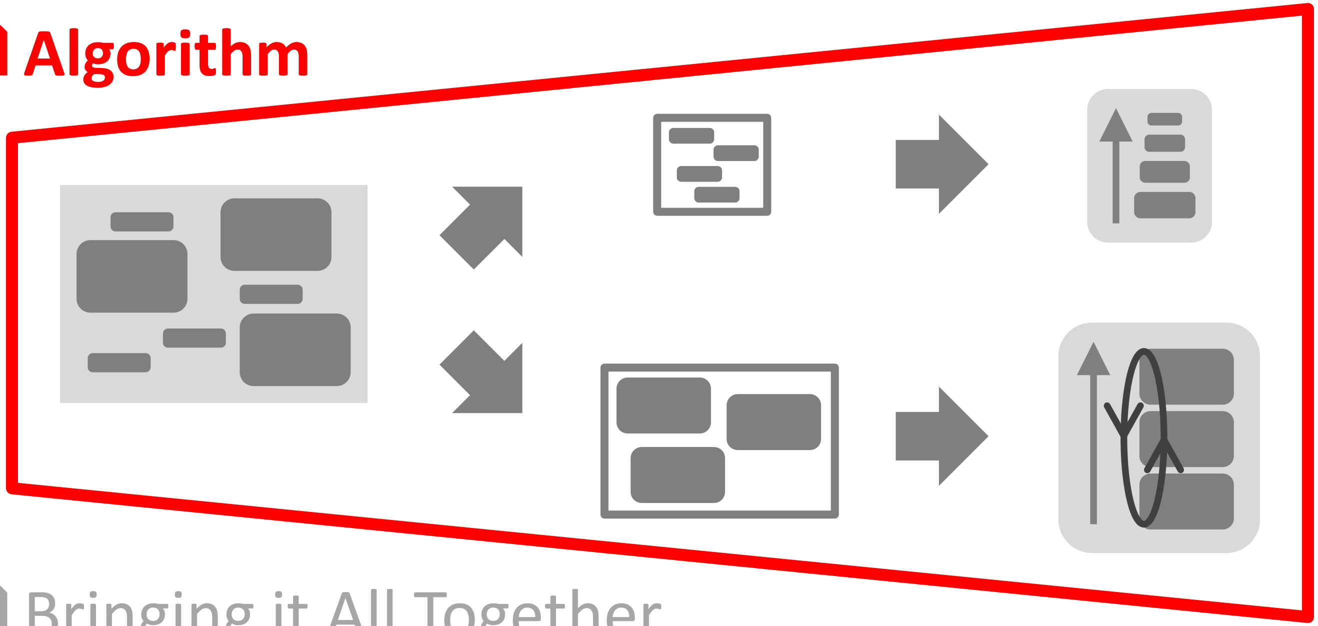
# Overview: Thread Cluster Memory Scheduling

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



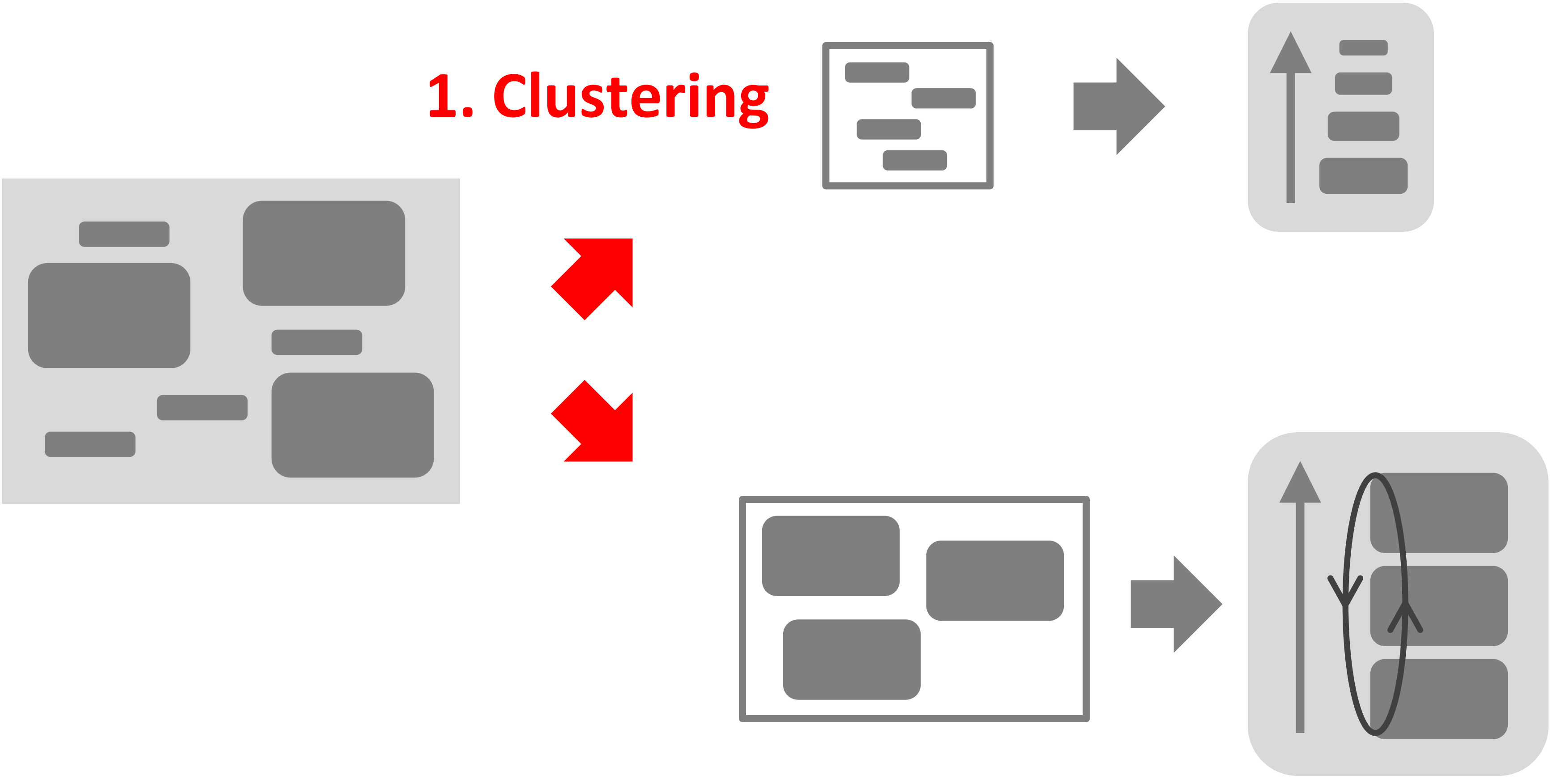
# Outline

- ❑ Motivation & Insights
- ❑ Overview
- ❑ **Algorithm**



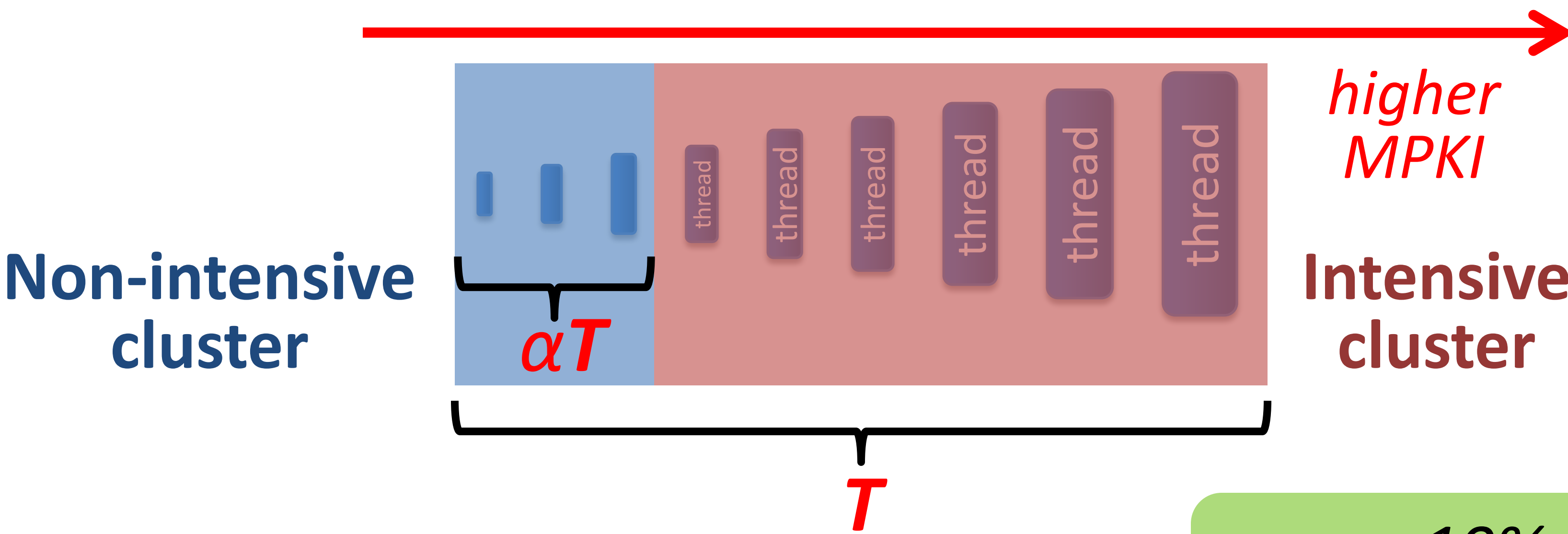
- ❑ Bringing it All Together
- ❑ Evaluation
- ❑ Conclusion

# TCM Outline



# Clustering Threads

**<u>Step1</u>** Sort threads by **MPKI** (misses per kiloinstruction)

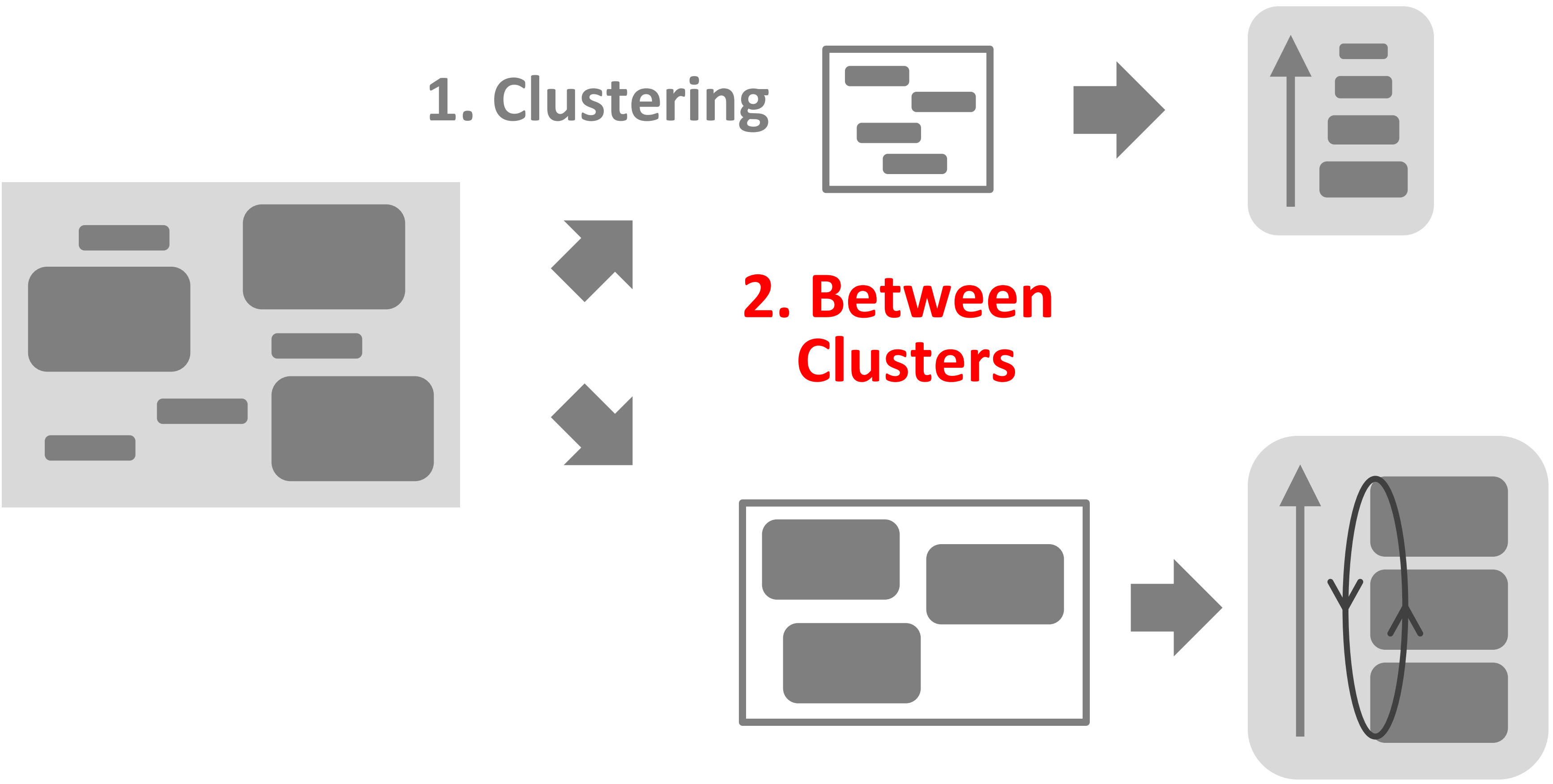



***T*** **=** Total ***memory bandwidth usage***

***α** < 10%*
***ClusterThreshold***

**<u>Step2</u>** Memory bandwidth usage $\alpha T$ divides clusters

# TCM Outline

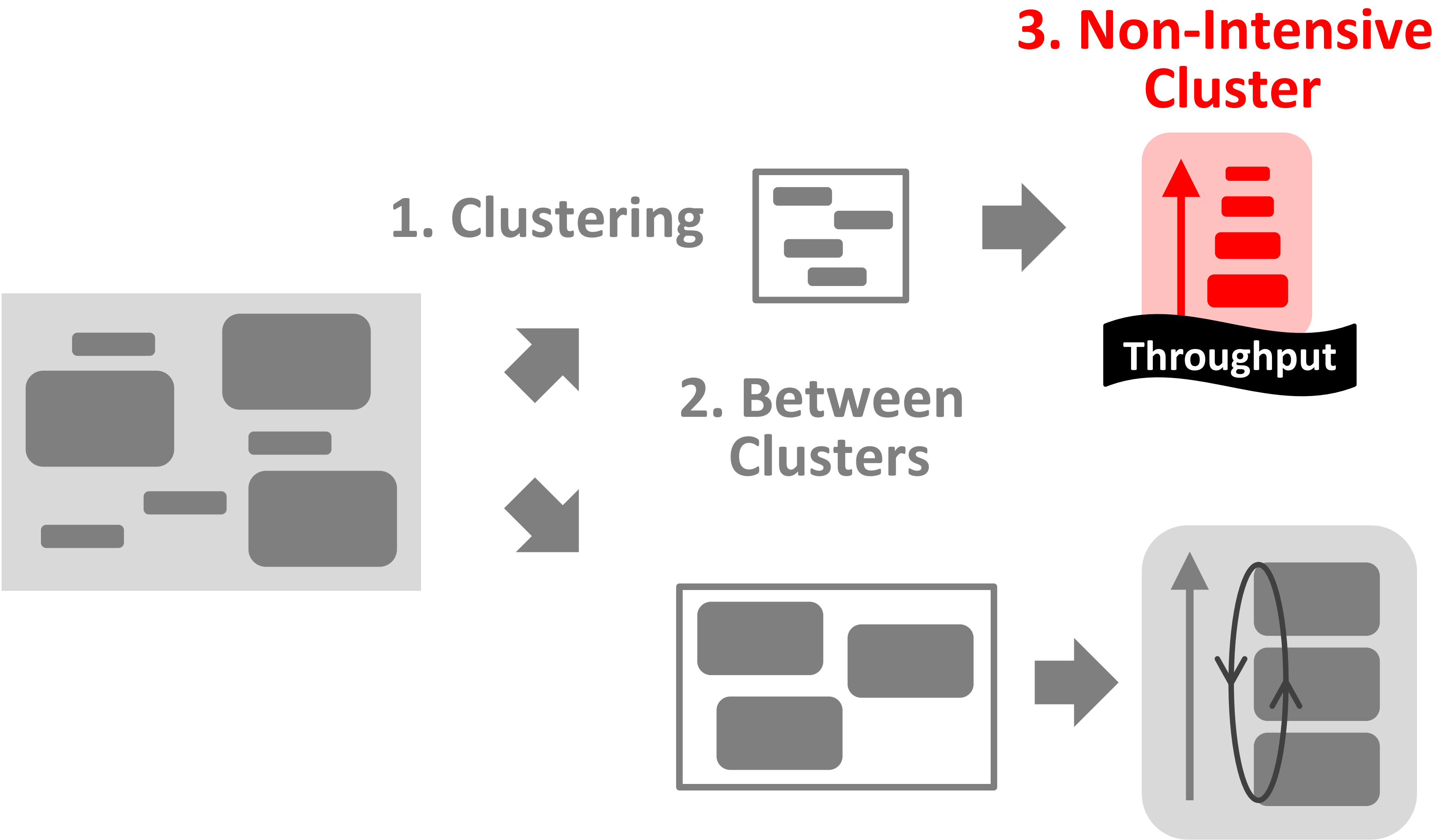


# Prioritization Between Clusters

***Prioritize non-intensive cluster***

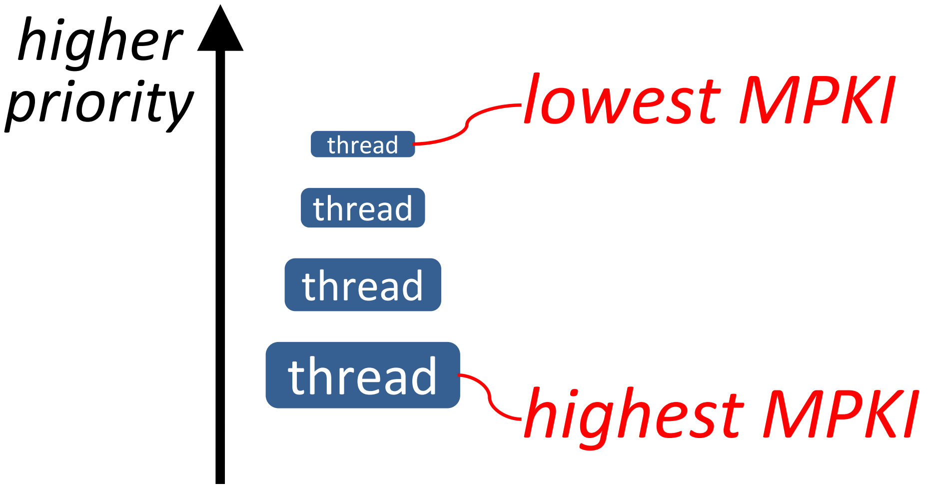

- **Increases system throughput**
  - Non-intensive threads have greater potential for making progress
- **Does not degrade fairness**
  - Non-intensive threads are “light”
  - Rarely interfere with intensive threads

# TCM Outline


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

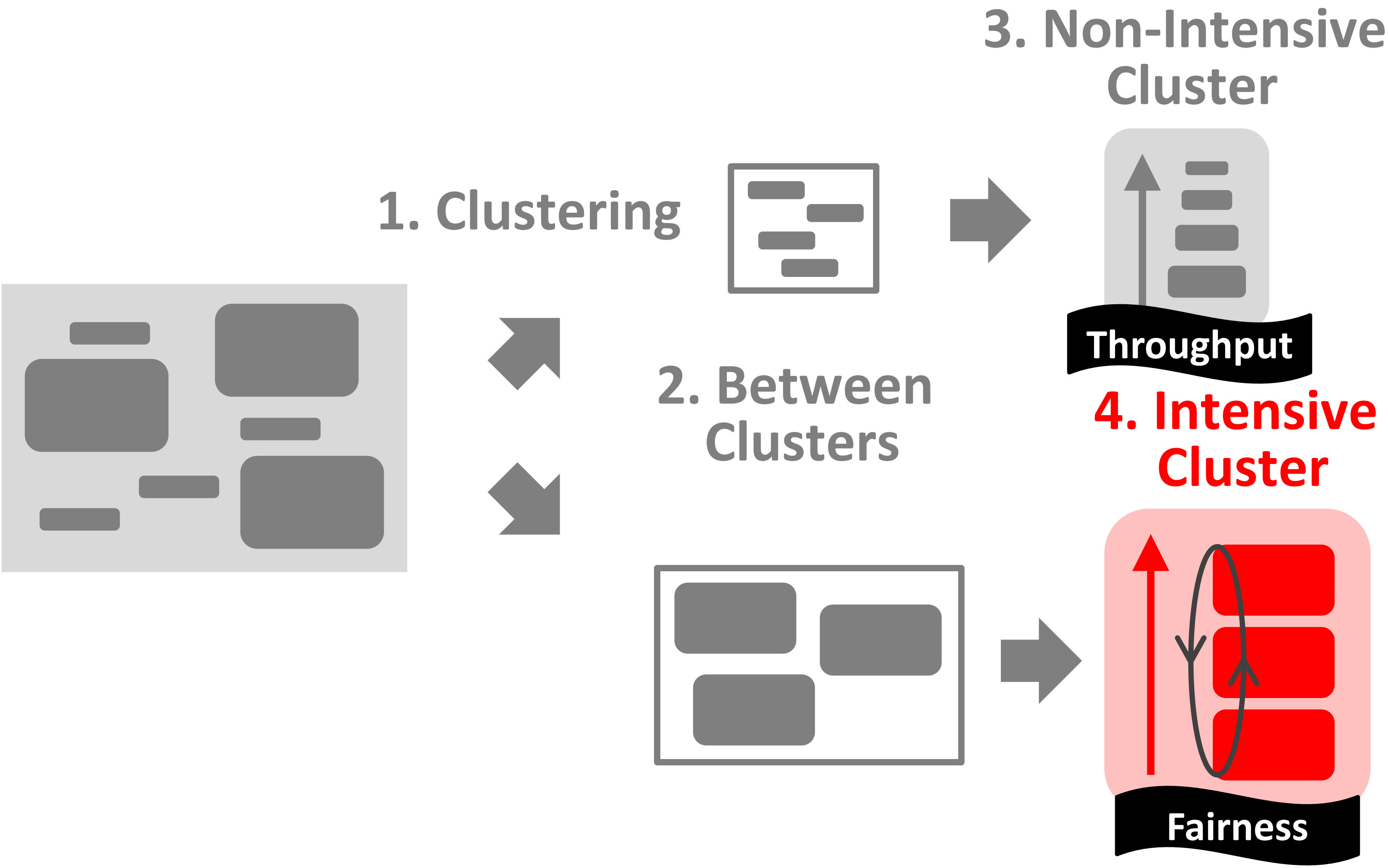
# Non-Intensive Cluster

***Prioritize threads according to MPKI***




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

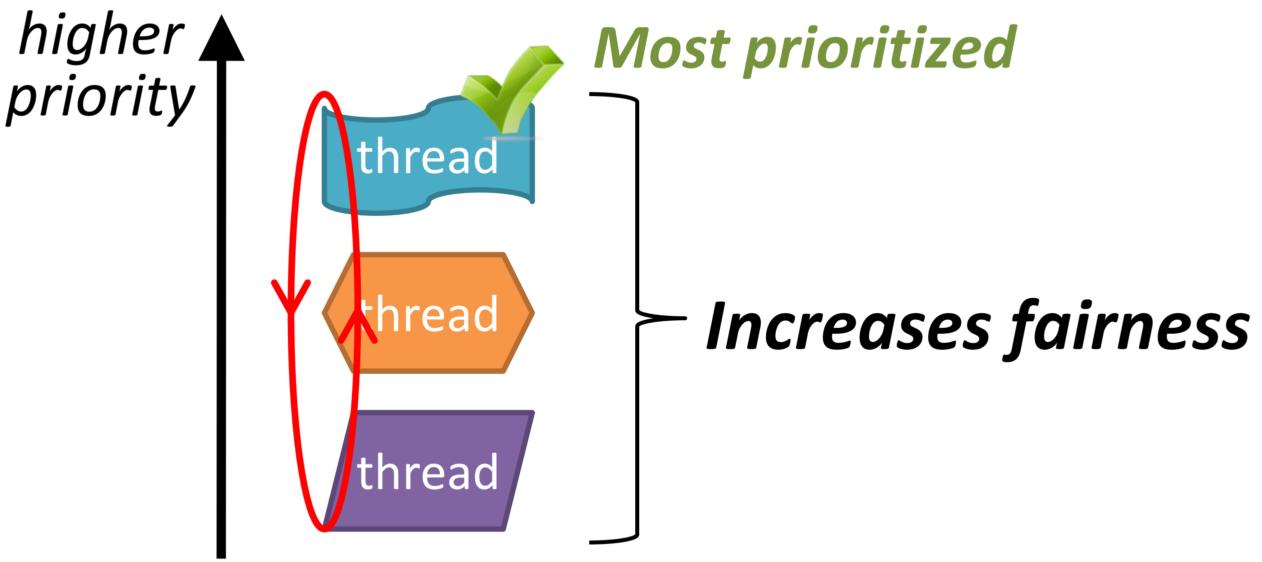
# TCM Outline



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

# Intensive Cluster

***Periodically shuffle the priority of threads***



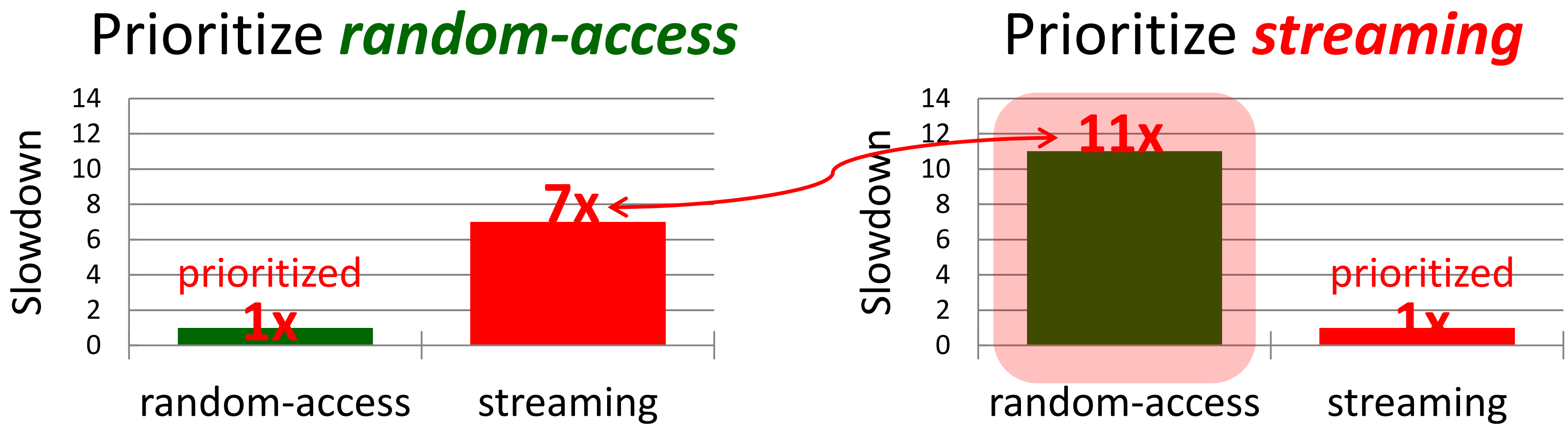

- Is treating all threads equally good enough?
- ***BUT:*** *Equal turns ≠ Same slowdown*

# Case Study: A Tale of Two Threads

**Case Study:** Two intensive threads contending

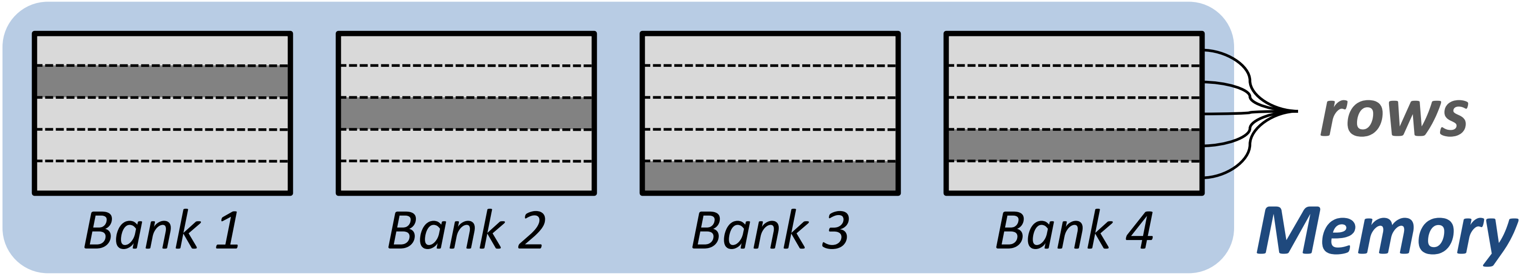
1. ***random-access***
2. ***streaming***

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

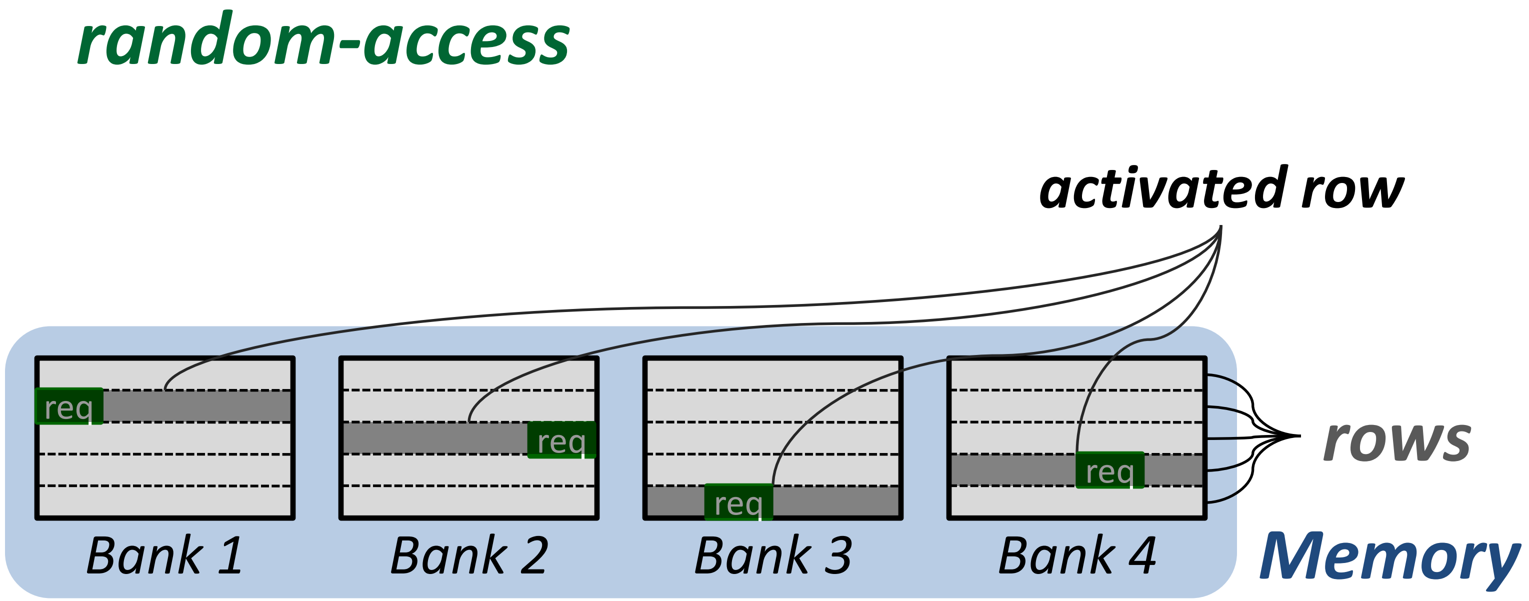



***random-access*** thread is more easily slowed down

# Why are Threads Different?

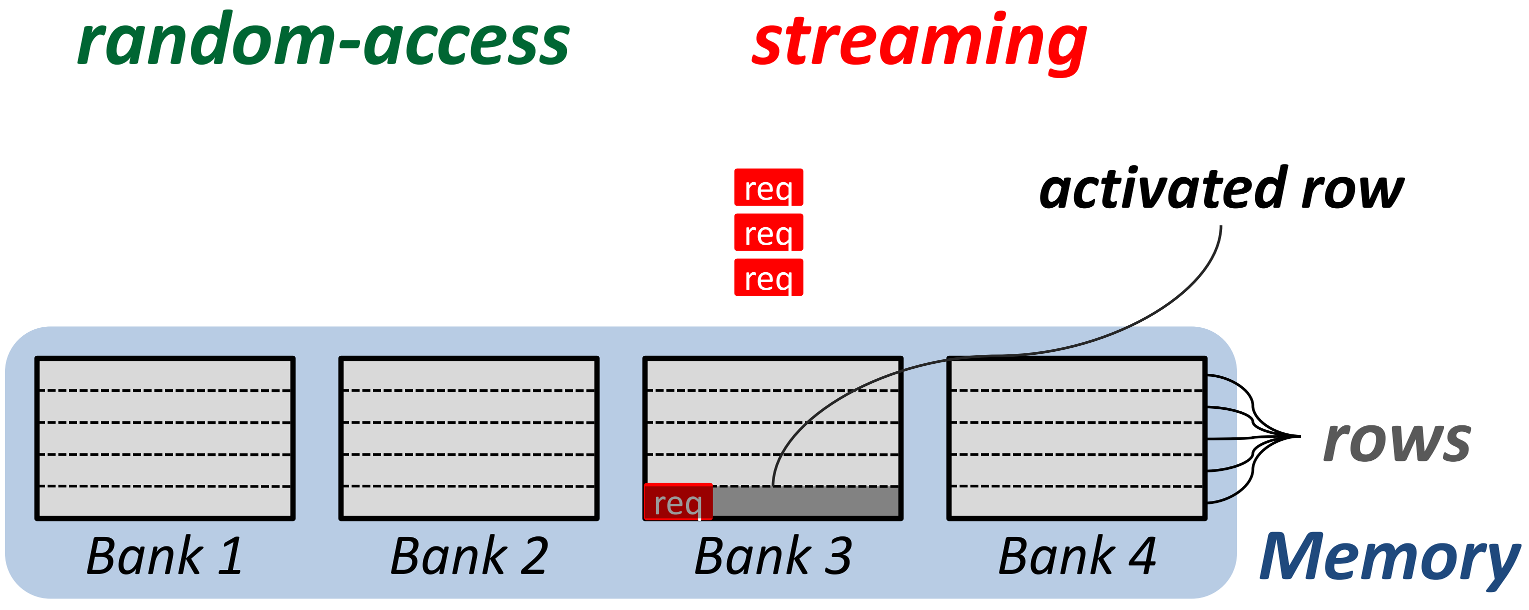


# Why are Threads Different?




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

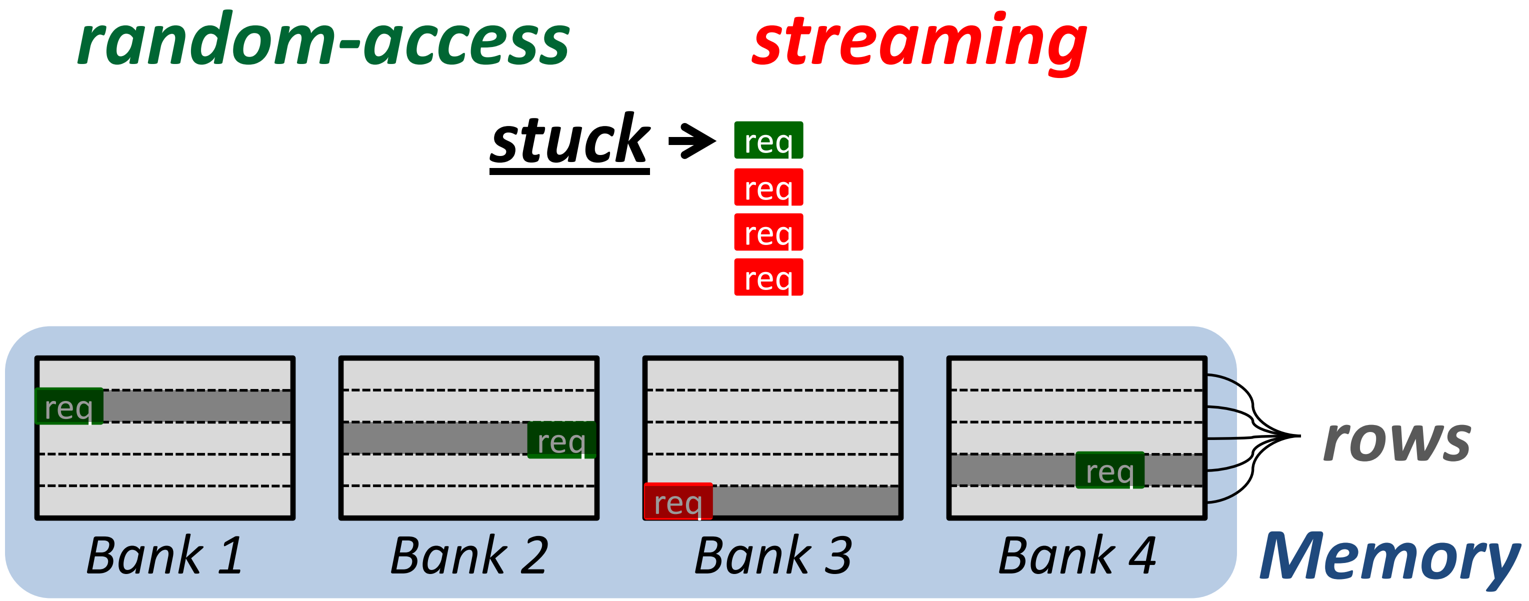
# Why are Threads Different?




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

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

# Why are Threads Different?

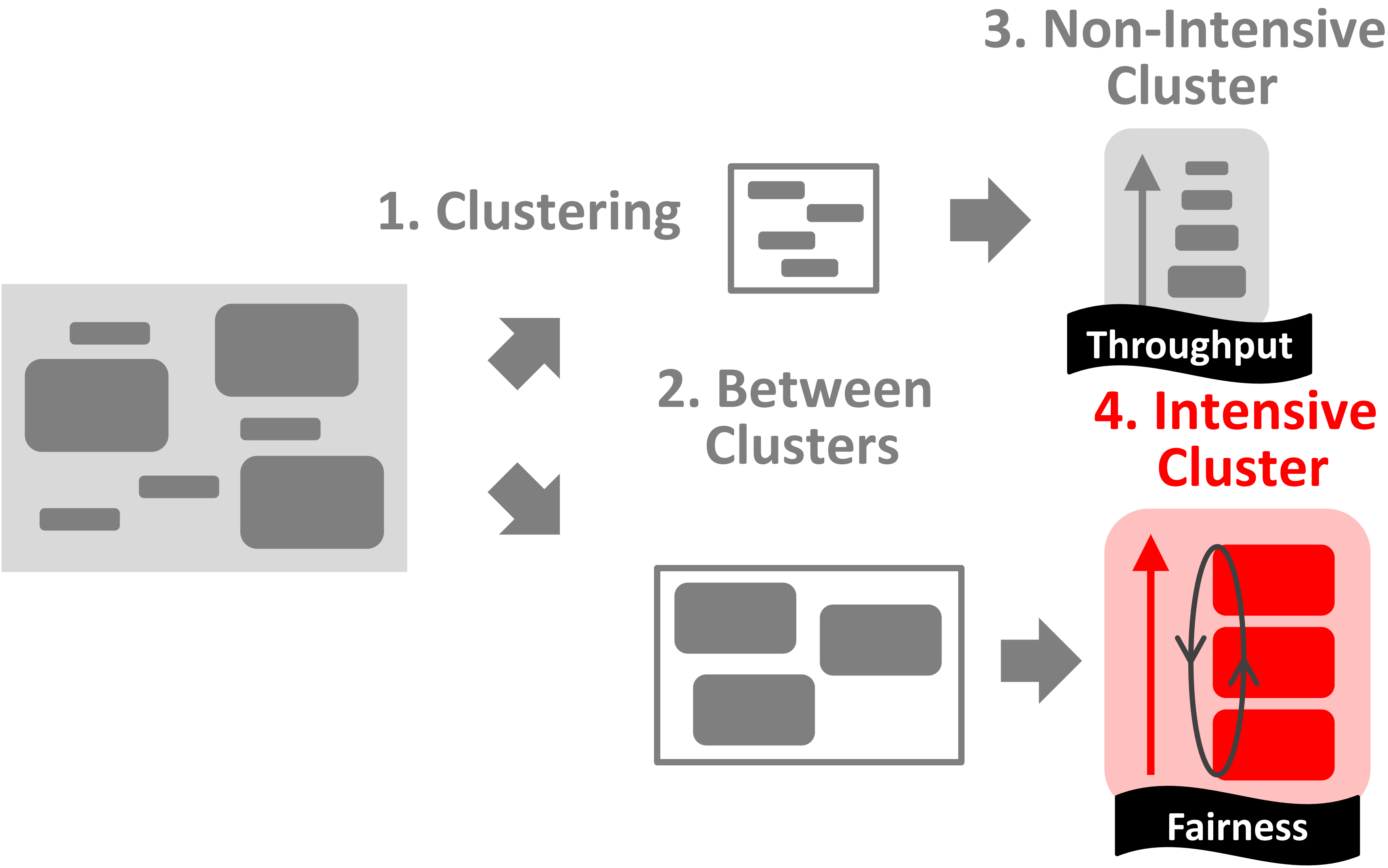



- All requests parallel
- High **bank-level parallelism**

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

***Vulnerable to interference***

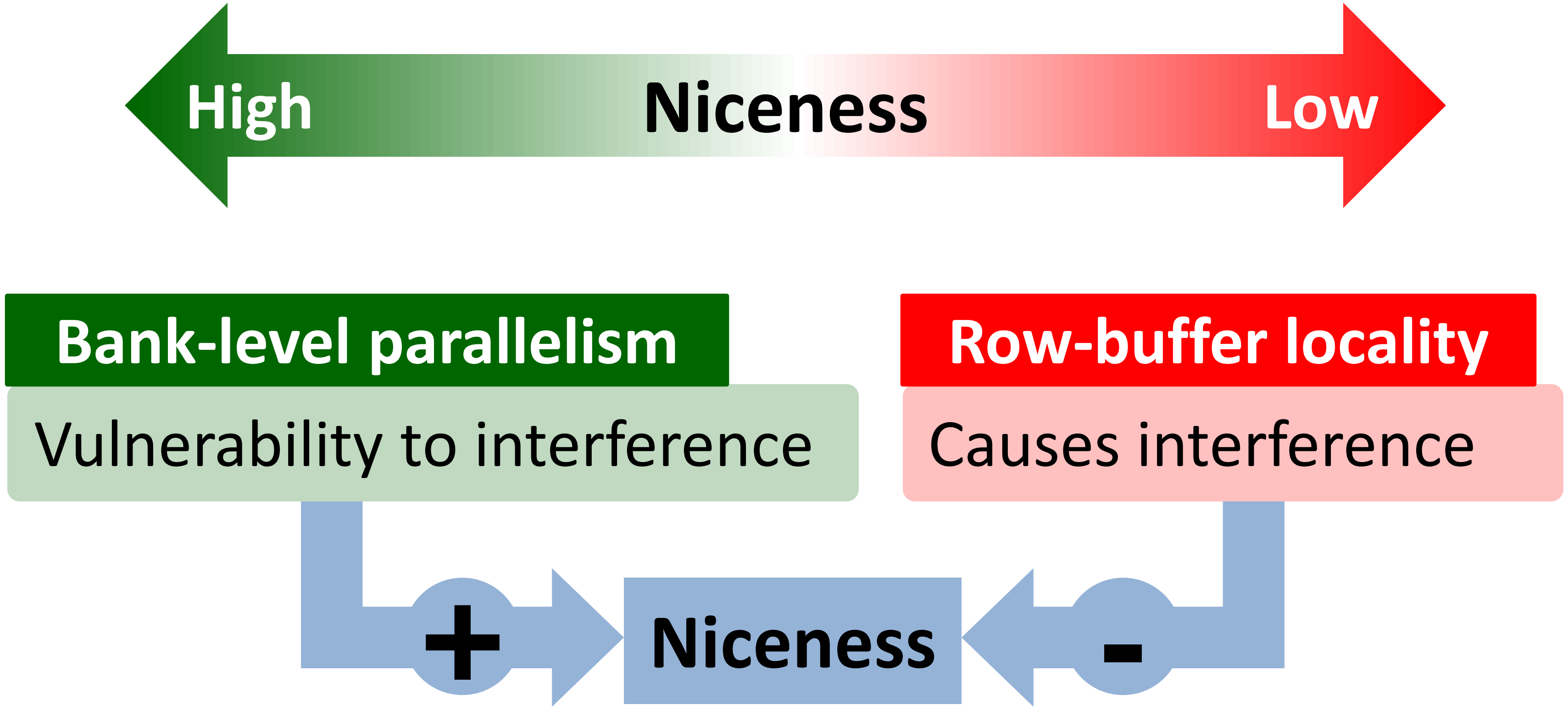
# TCM Outline



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

# Niceness

***How to quantify difference between threads?***

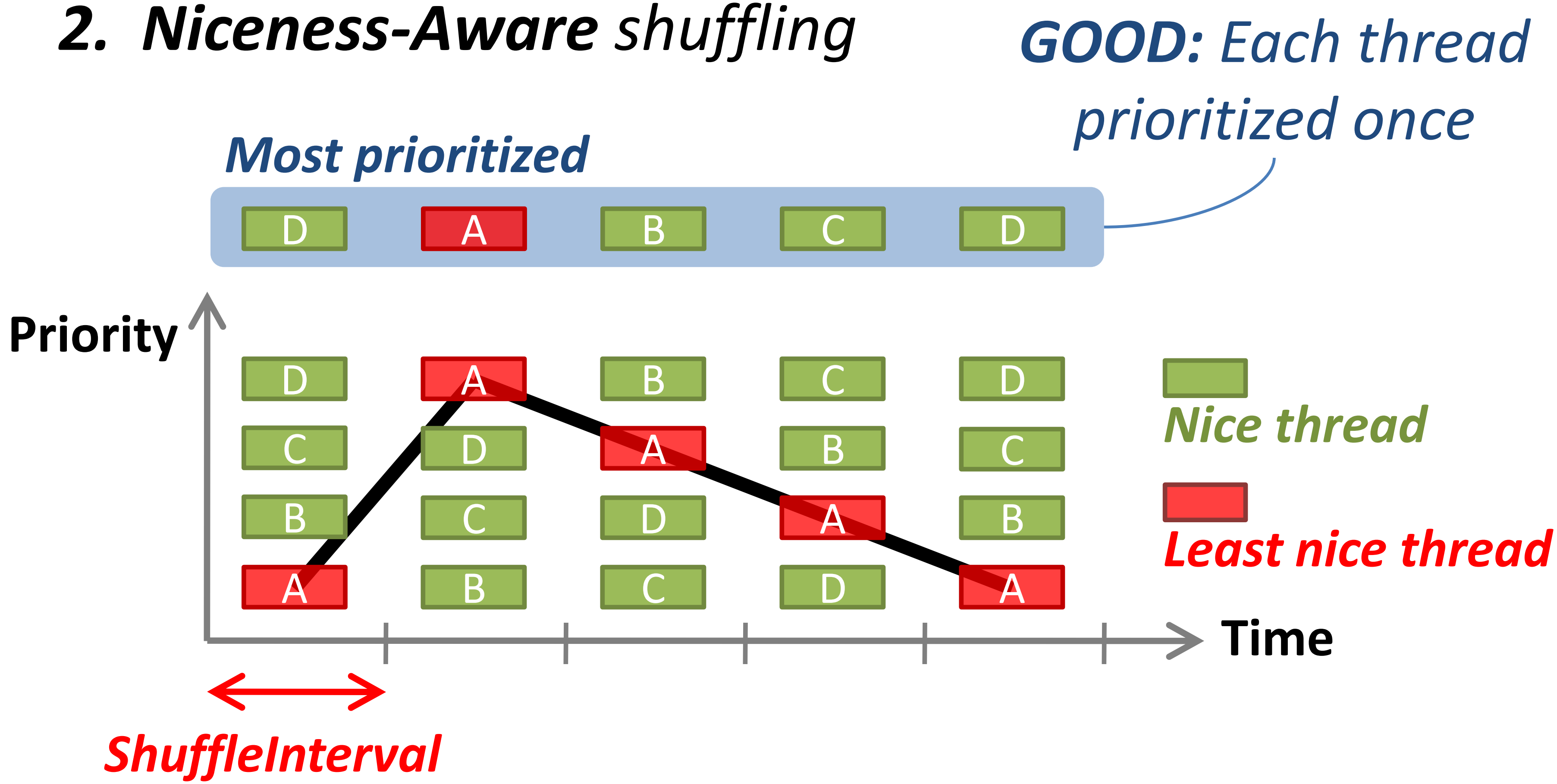


# Shuffling: Round-Robin vs. Niceness-Aware

1. ***Round-Robin*** *shuffling* ← *What can go wrong?*
2. ***Niceness-Aware*** *shuffling*

# Shuffling: Round-Robin vs. Niceness-Aware

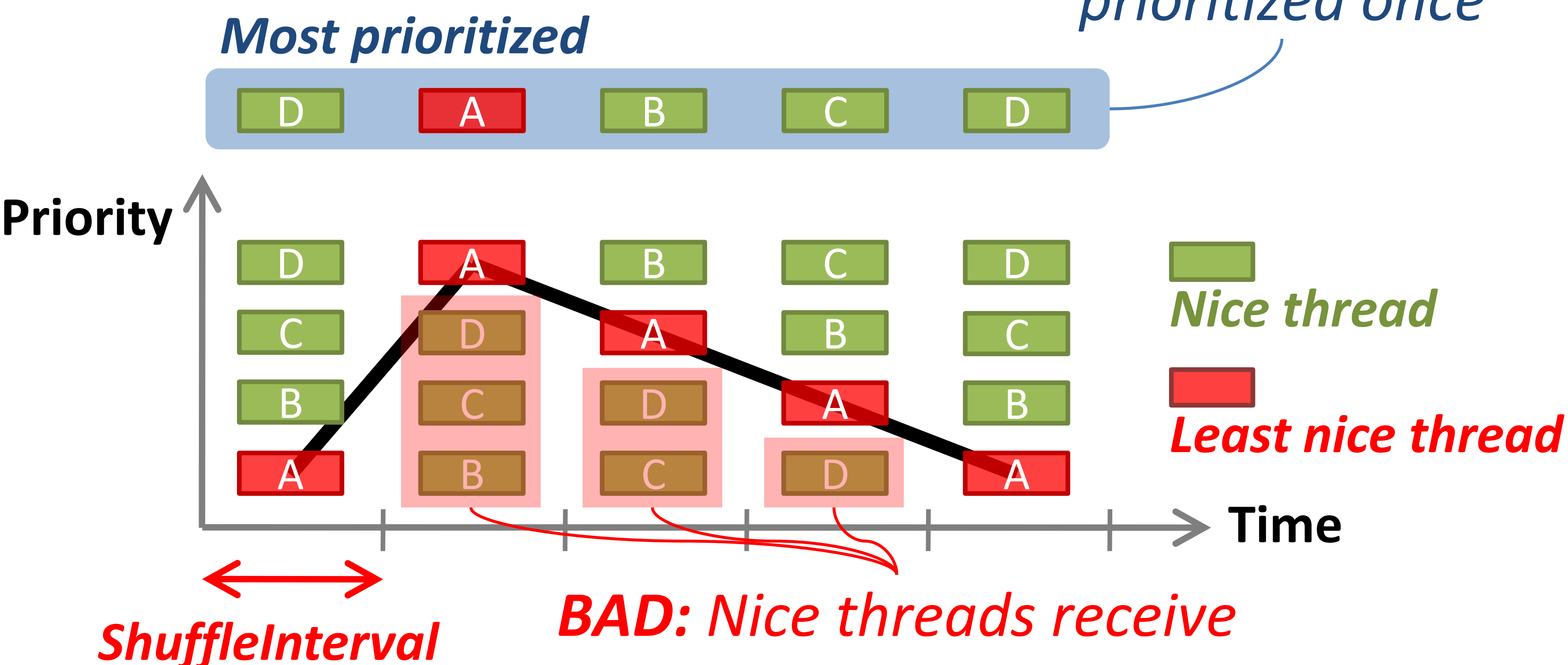
1. ***Round-Robin** shuffling* ← *What can go wrong?*
2. ***Niceness-Aware** shuffling*



# Shuffling: Round-Robin vs. Niceness-Aware

1. ***Round-Robin*** *shuffling* ← *What can go wrong?*
2. ***Niceness-Aware*** *shuffling*

***GOOD:*** *Each thread prioritized once*



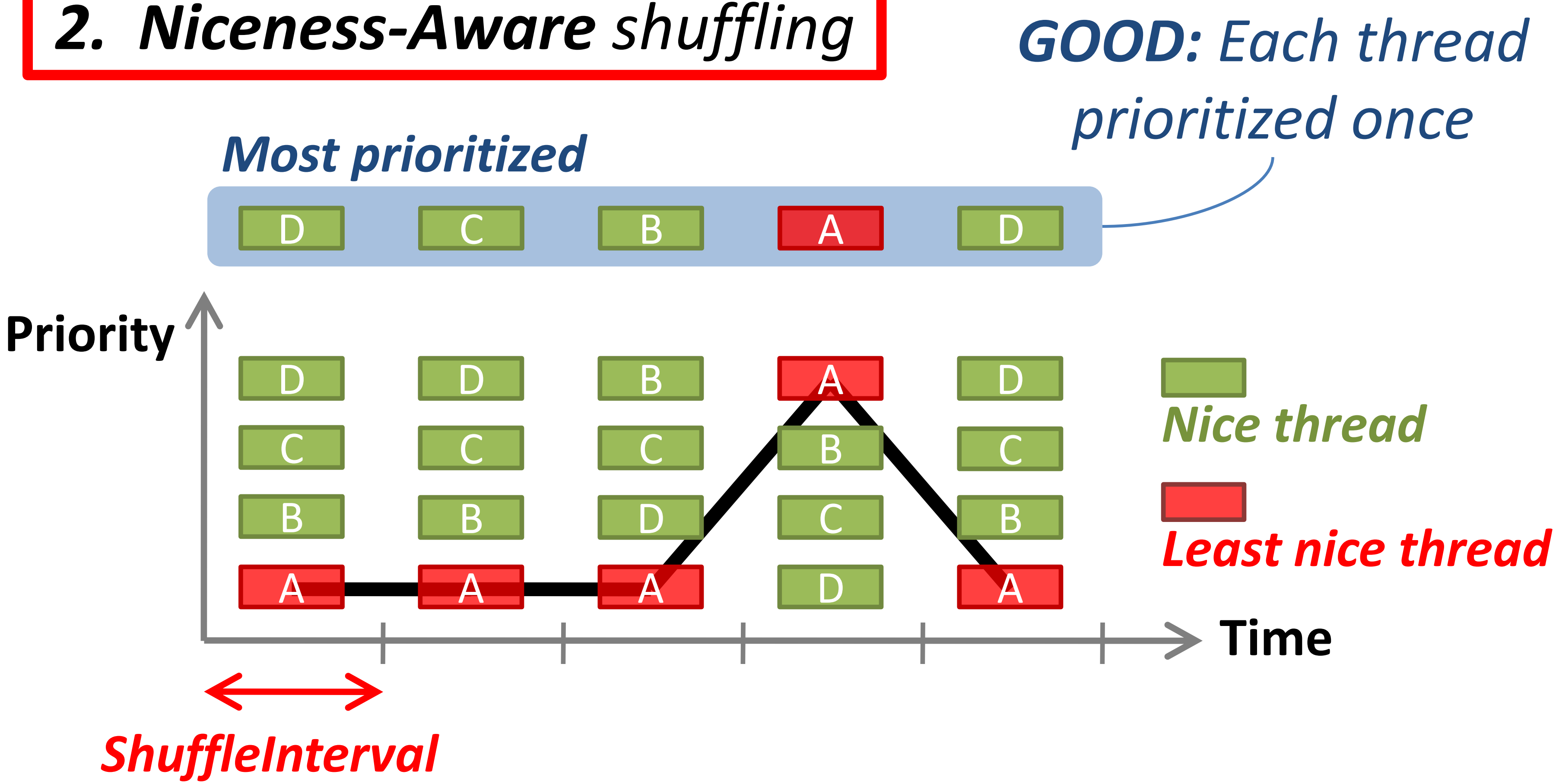

***BAD:*** *Nice threads receive lots of interference*

# Shuffling: Round-Robin vs. Niceness-Aware

1. ***Round-Robin** shuffling*
2. ***Niceness-Aware** shuffling*

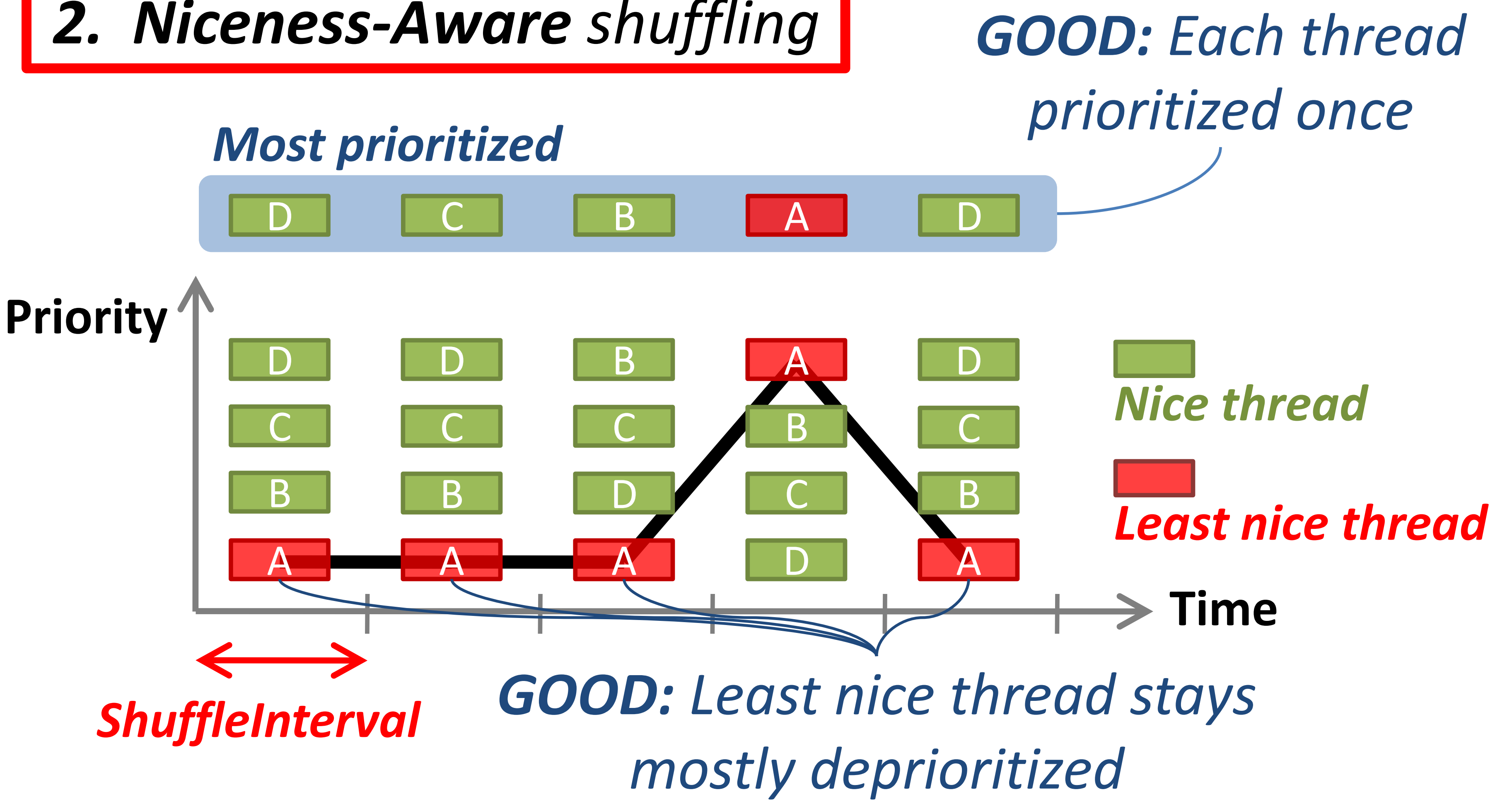
# Shuffling: Round-Robin vs. Niceness-Aware

1. ***Round-Robin*** *shuffling*
2. ***Niceness-Aware*** *shuffling*

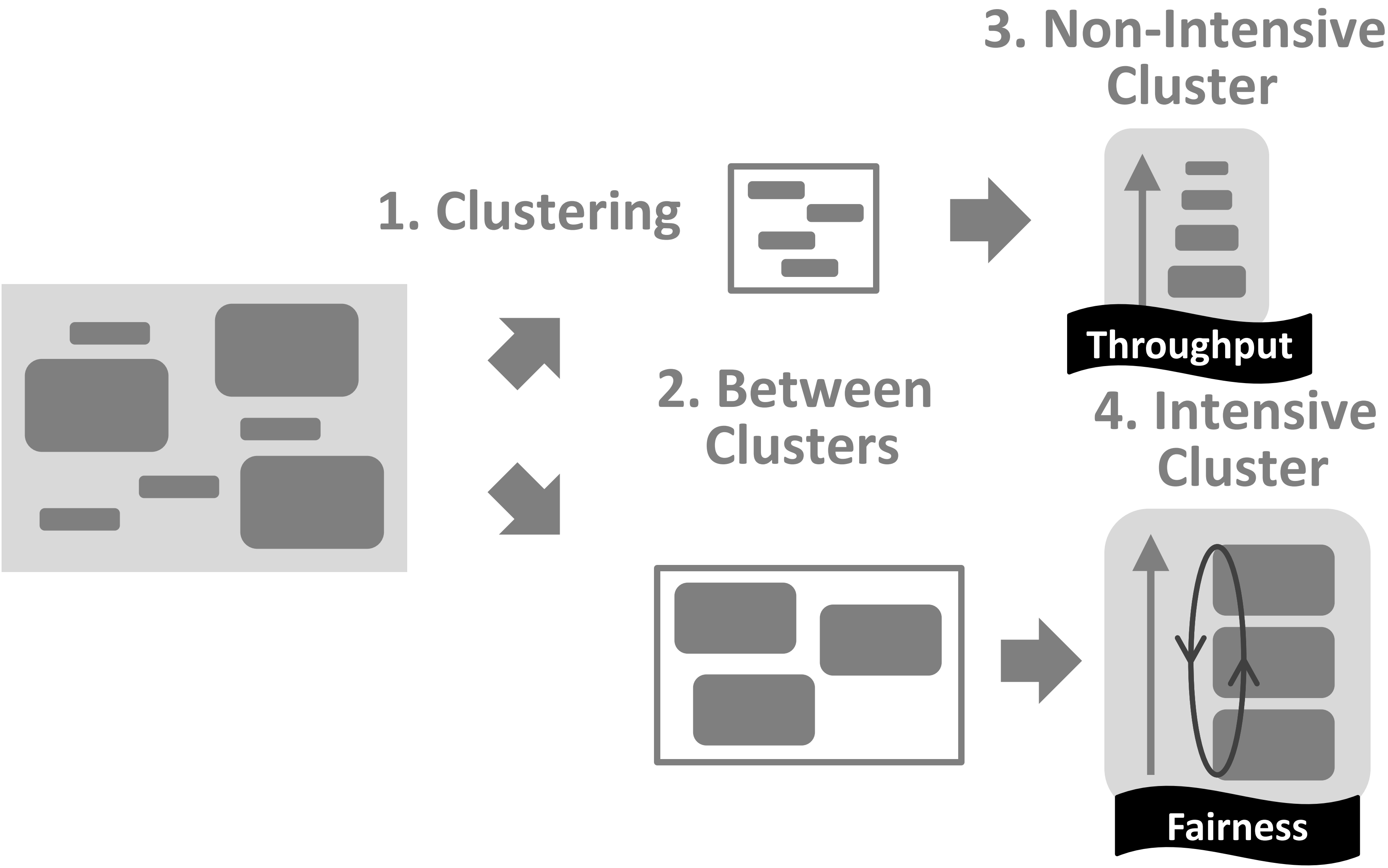


# Shuffling: Round-Robin vs. Niceness-Aware

1. ***Round-Robin** shuffling*
2. ***Niceness-Aware** shuffling*

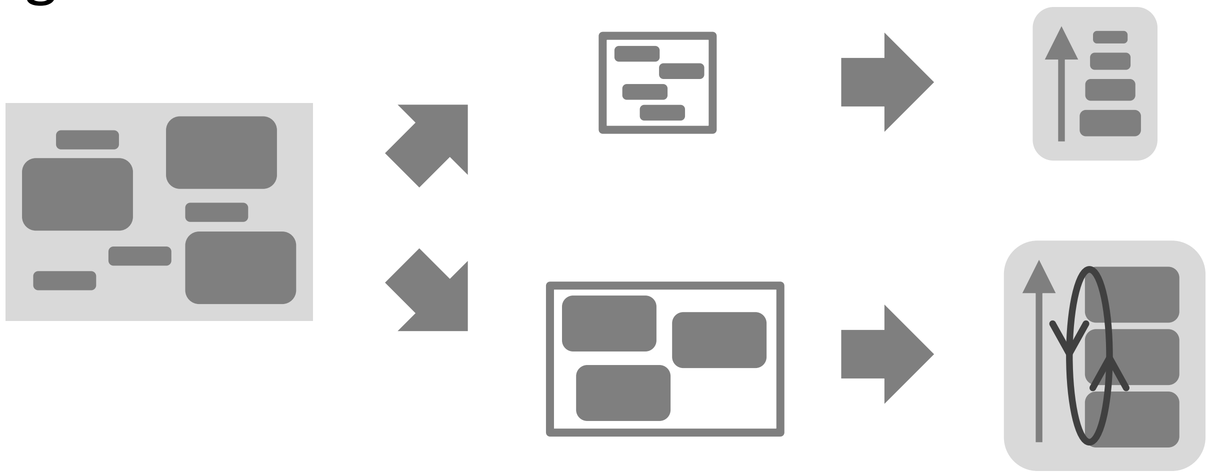


# TCM Outline


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

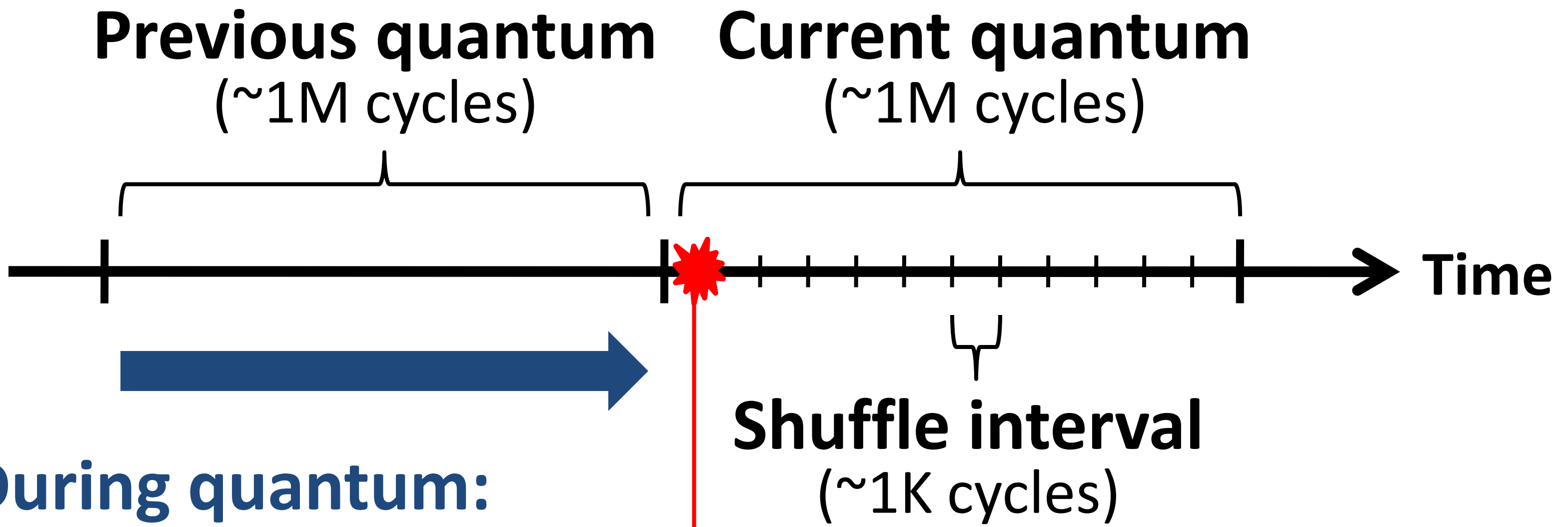
# Outline

- ❑ Motivation & Insights
- ❑ Overview
- ❑ Algorithm



- ❑ **Bringing it All Together**
- ❑ Evaluation
- ❑ Conclusion

# 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

# Implementation Costs

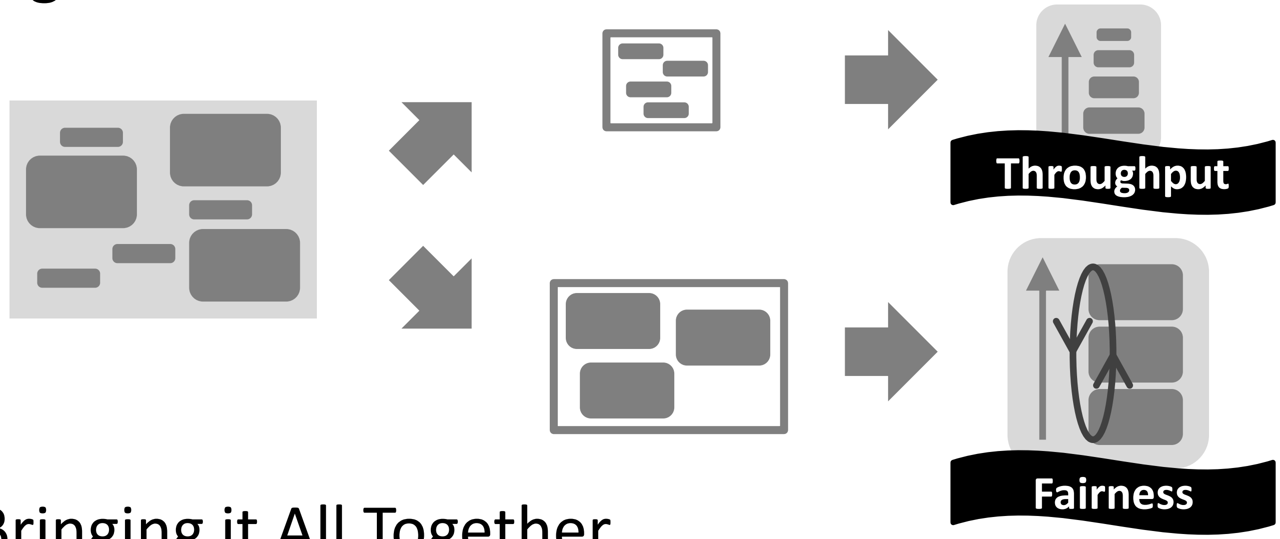
***Required storage at memory controller*** *(24 cores)*

| 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

# Outline

- ❑ Motivation & Insights
- ❑ Overview
- ❑ Algorithm




- ❑ Bringing it All Together
- ❑ **Evaluation**
- ❑ Conclusion

# Metrics & Methodology

- **Metrics**

**System throughput**

$$Weighted\ Speedup = \sum_i \frac{IPC_i^{shared}}{IPC_i^{alone}}$$

**Unfairness**

$$Maximum\ Slowdown = \max_i \frac{IPC_i^{alone}}{IPC_i^{shared}}$$

- **Methodology**
  - Core model
    - 4 GHz processor, 128-entry instruction window
    - 512 KB/core L2 cache
  - Memory model: DDR2
  - 96 multiprogrammed SPEC CPU2006 workloads

# 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

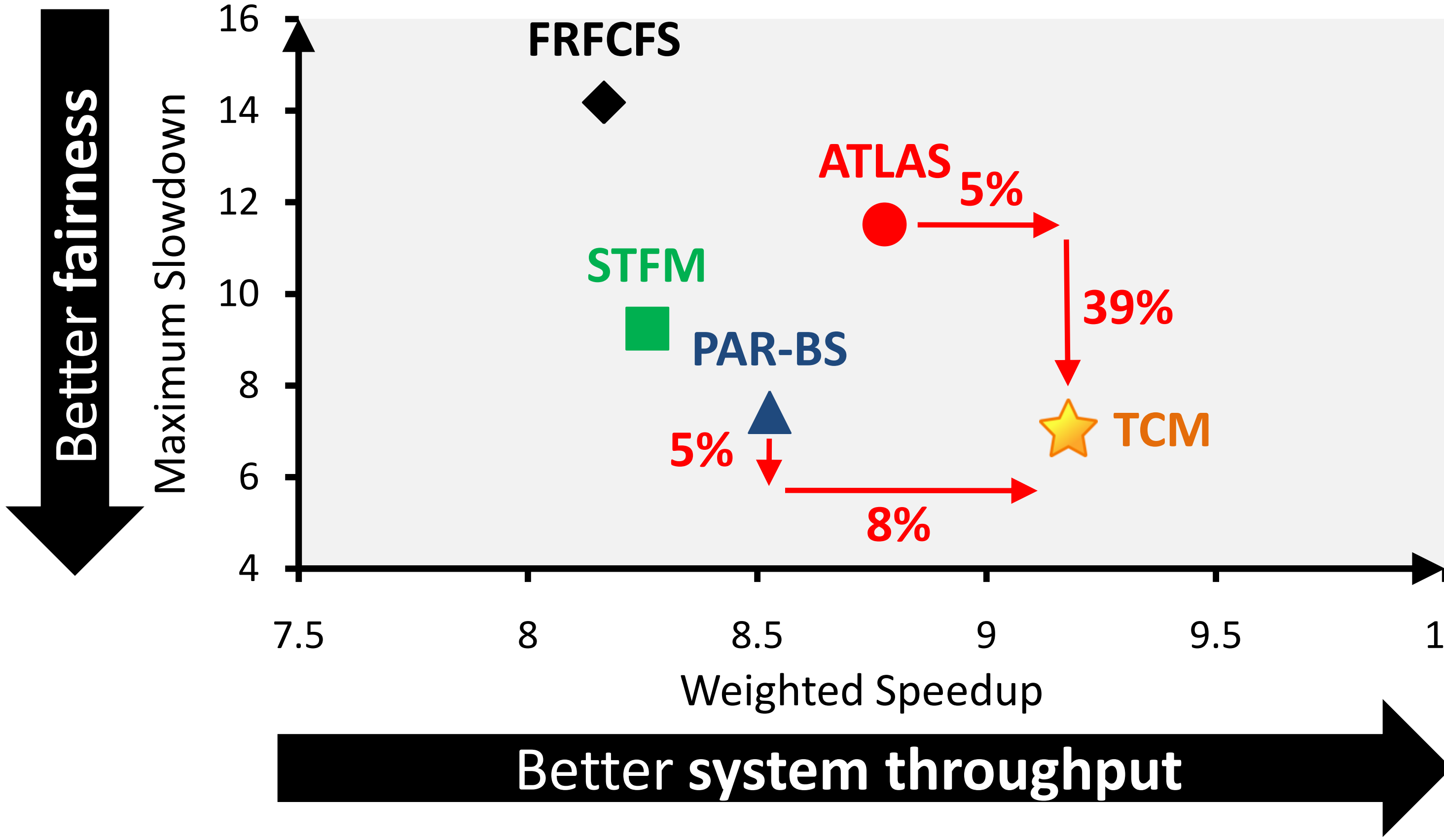
- Non-intensive threads not always prioritized ➔ Low throughput

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

- Most intensive thread starves ➔ Low fairness

# Results: Fairness vs. Throughput

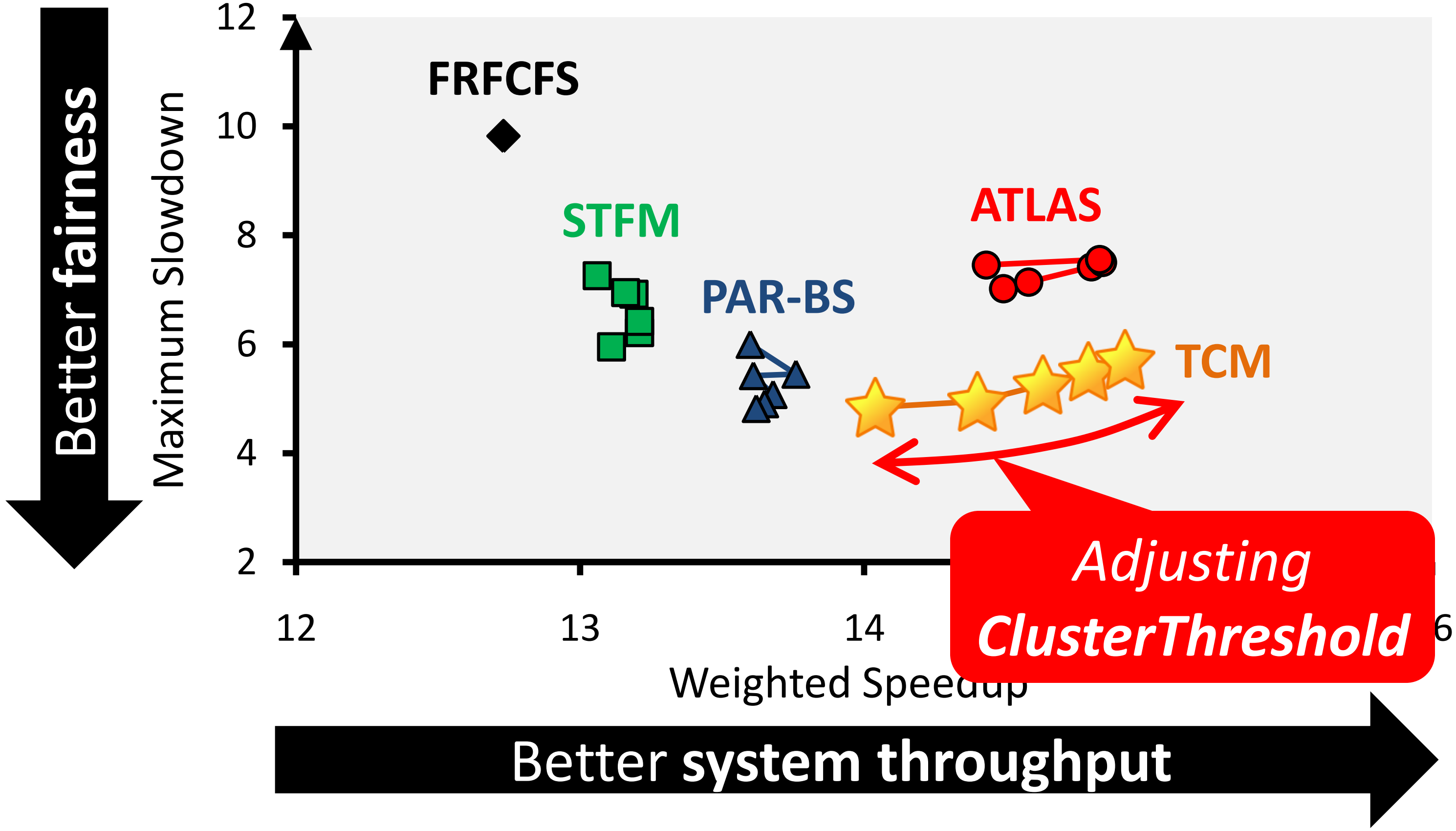
**Averaged over 96 workloads**




*TCM provides best fairness and system throughput*

# Results: Fairness-Throughput Tradeoff

**When configuration parameter is varied…**




*TCM allows robust fairness-throughput tradeoff*

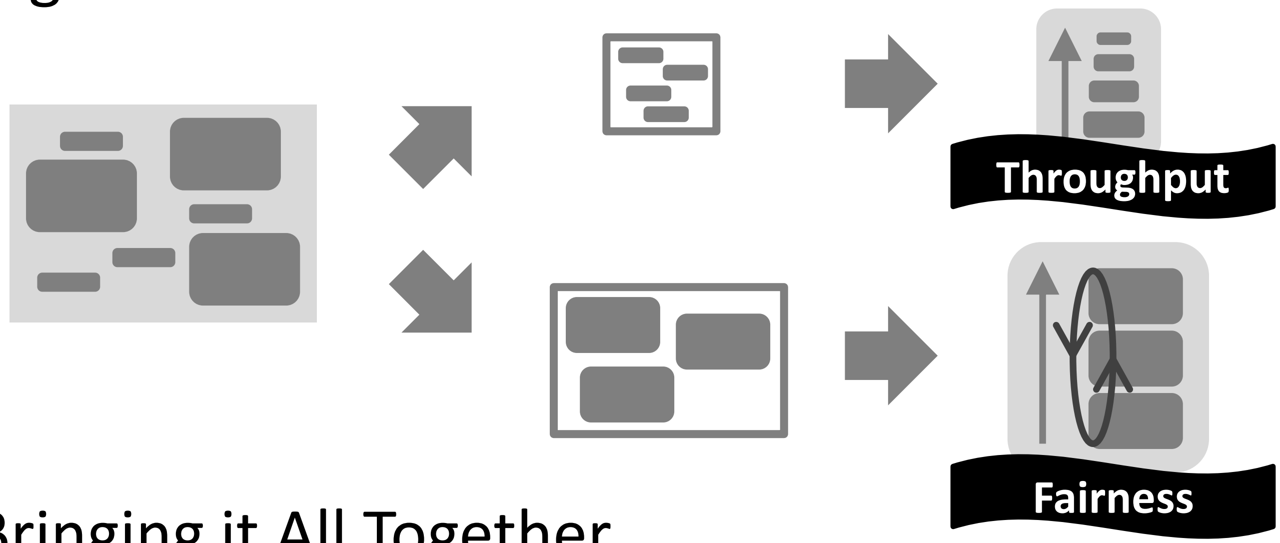
# Operating System Support

- ***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

# Outline

- ❑ Motivation & Insights
- ❑ Overview
- ❑ Algorithm




- ❑ Bringing it All Together
- ❑ Evaluation
- ❑ **Conclusion**

# 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*

# THANK YOU

# Thread Cluster Memory Scheduling:

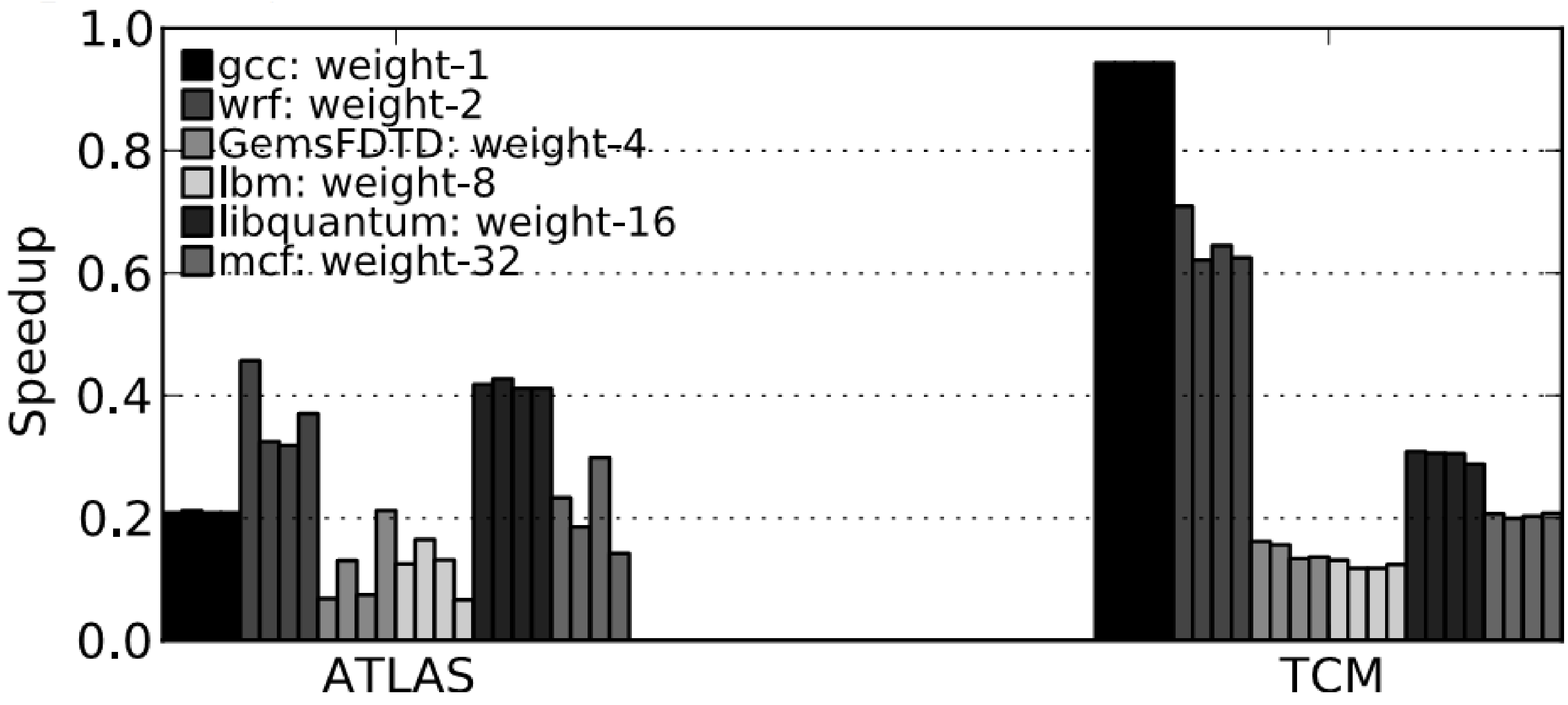
## Exploiting Differences in Memory Access Behavior

**Yoongu Kim**
Michael Papamichael
Onur Mutlu
Mor Harchol-Balter

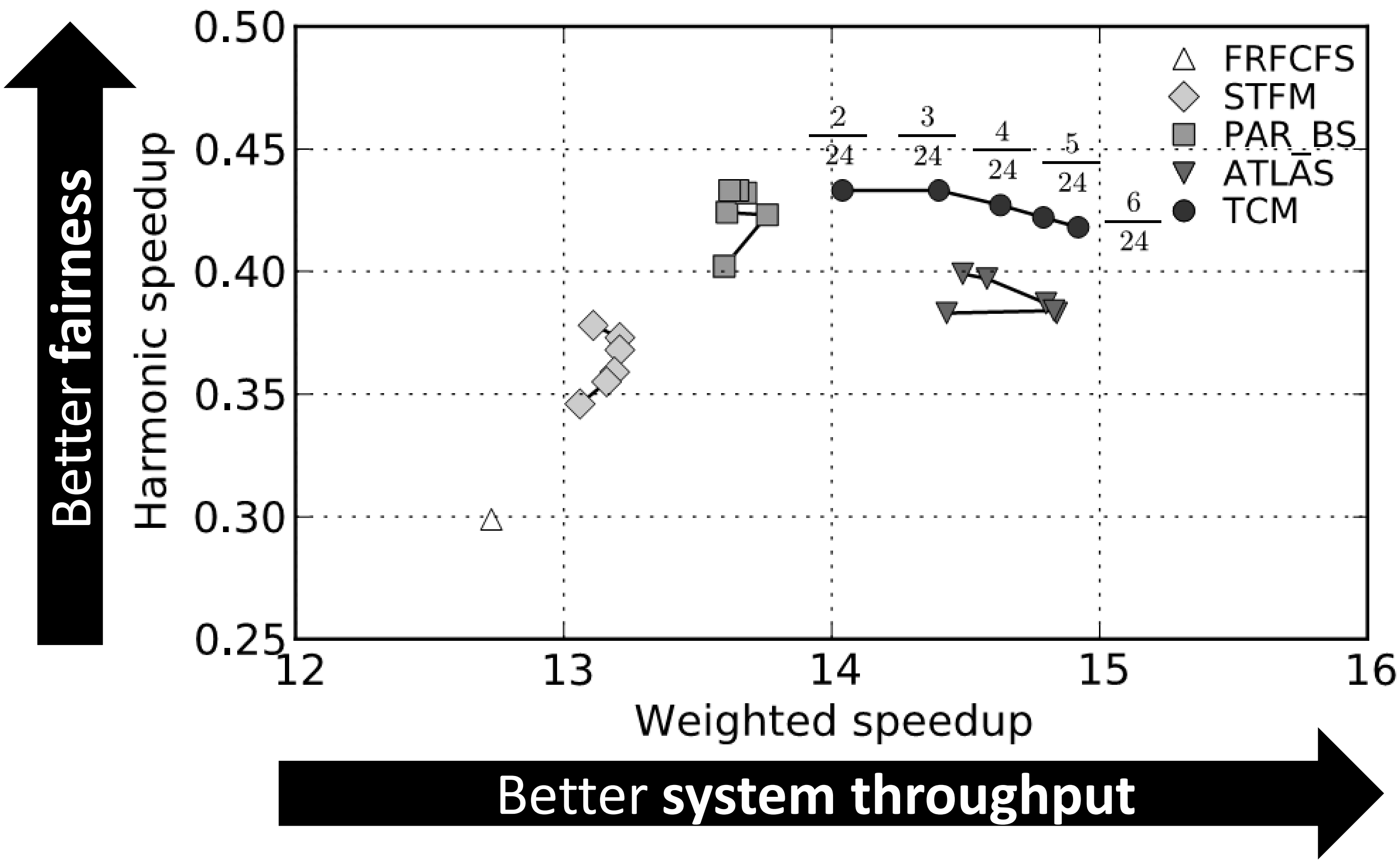
Carnegie Mellon

# Thread Weight Support

- Even if heaviest weighted thread happens to be the most intensive thread…
  - Not prioritized over the least intensive thread



# Harmonic Speedup



# Shuffling Algorithm Comparison

- Niceness-Aware shuffling
  - Average of maximum slowdown is lower
  - Variance of maximum slowdown is lower

| | Shuffling Algorithm | |
|---|---|---|
| | **Round-Robin** | **Niceness-Aware** |
| E(Maximum Slowdown) | 5.58 | 4.84 |
| VAR(Maximum Slowdown) | 1.61 | 0.85 |

# Sensitivity Results

| | ***ShuffleInterval*** (cycles) | | | |
|---|---|---|---|---|
| | 500 | 600 | 700 | 800 |
| System Throughput | 14.2 | 14.3 | 14.2 | 14.7 |
| Maximum Slowdown | 6.0 | 5.4 | 5.9 | 5.5 |

| | ***Number of Cores*** | | | | |
|---|---|---|---|---|---|
| | 4 | 8 | 16 | 24 | 32 |
| System Throughput *(compared to ATLAS)* | 0% | 3% | 2% | 1% | 1% |
| Maximum Slowdown *(compared to ATLAS)* | -4% | -30% | -29% | -30% | -41% |