

# COTS Multicore Processors in Avionics Systems: Challenges and Solutions

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# Why Multi-Core Processors?

## Processor development trend

- Increasing overall performance by integrating multiple cores

## Embedded systems: Actively adopting multi-core CPUs

- **Automotive:**

- Freescale i.MX6 4-core CPU
- NVIDIA Tegra K1 platform

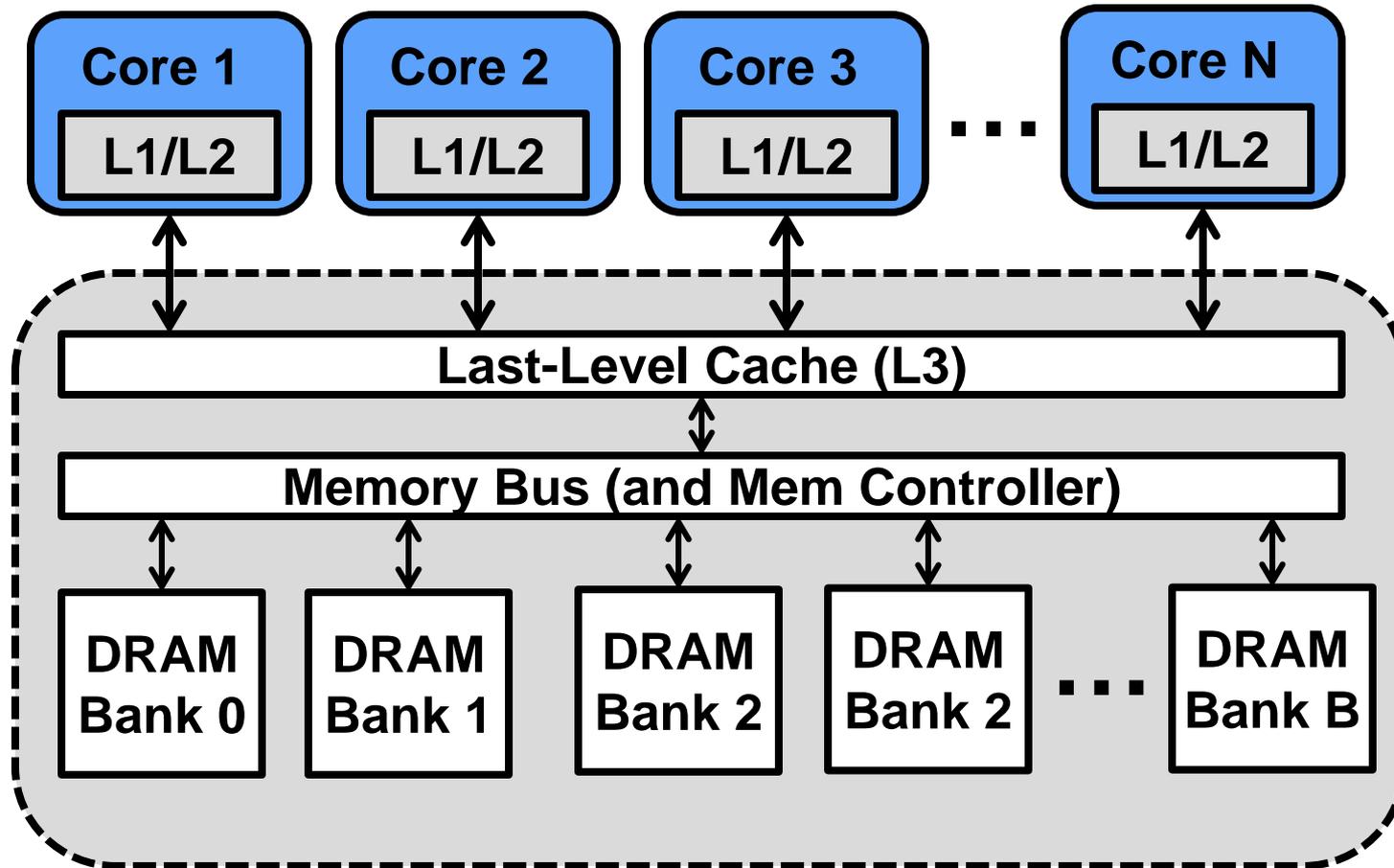


- **Avionics and defense:**

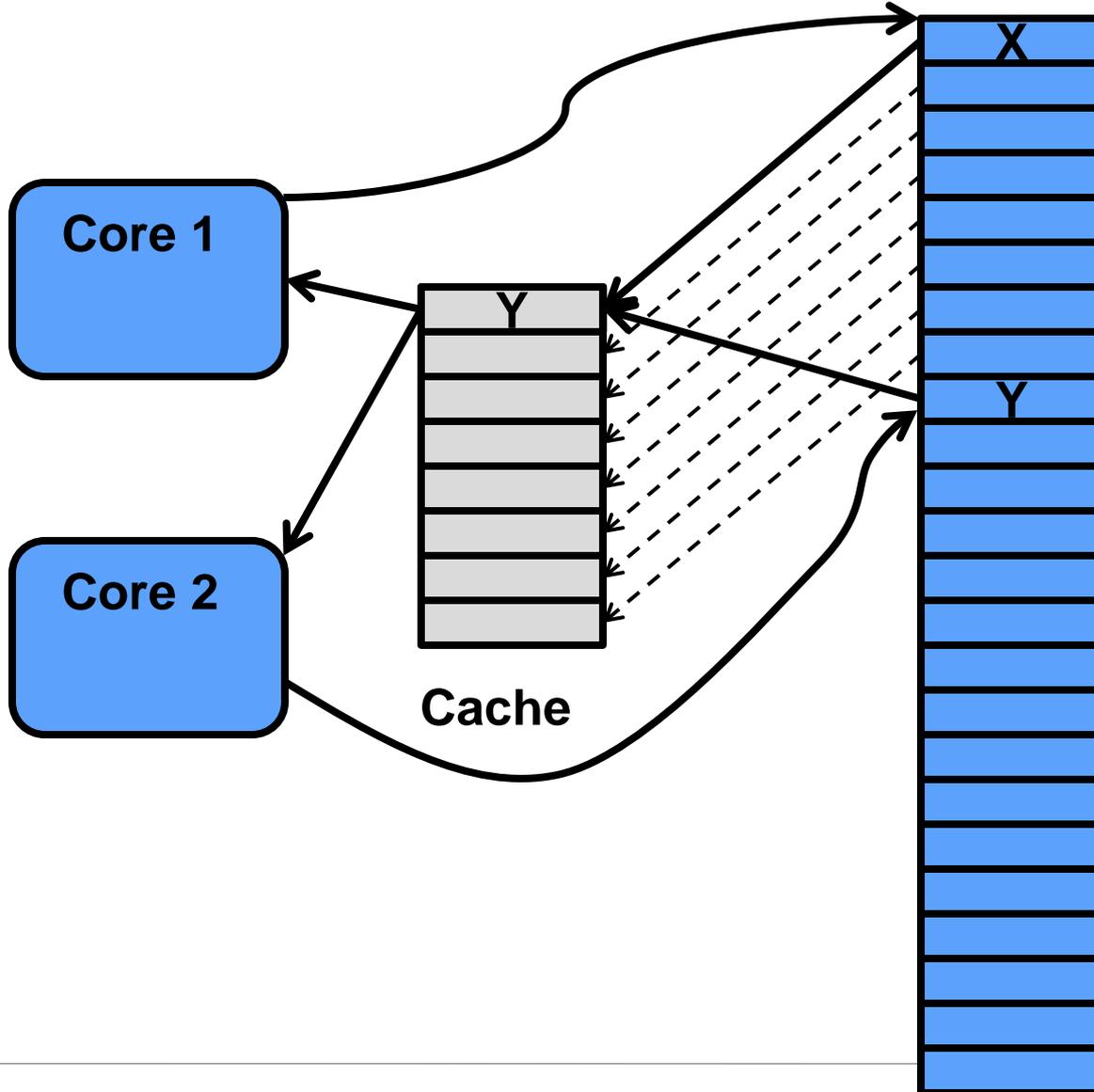
- Rugged Intel i7 single board computers
- Freescale P4080 8-core CPU



# Shared Hardware: Multicore Memory System

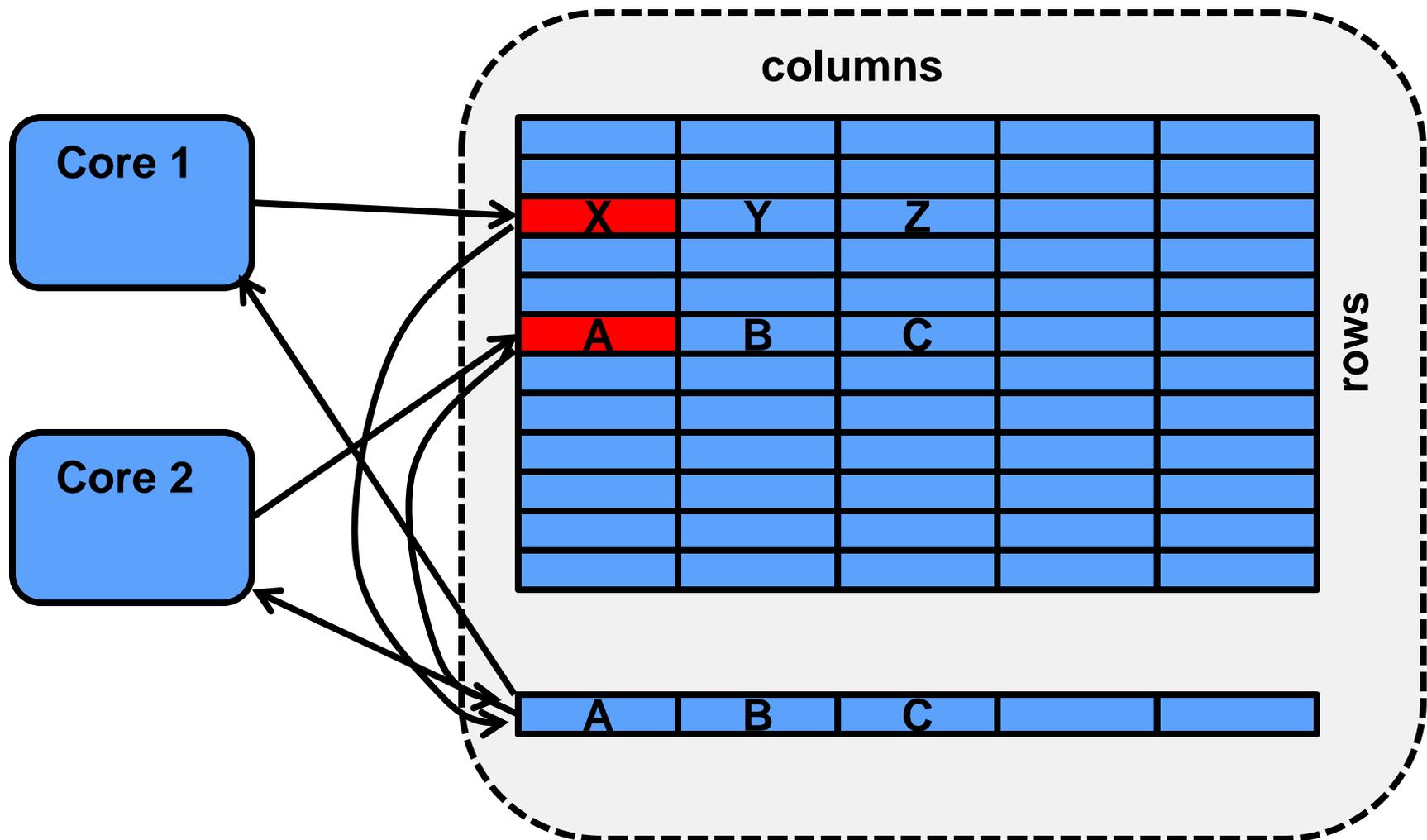


# Cache Interference Across Cores



# Bank Interference Across Cores

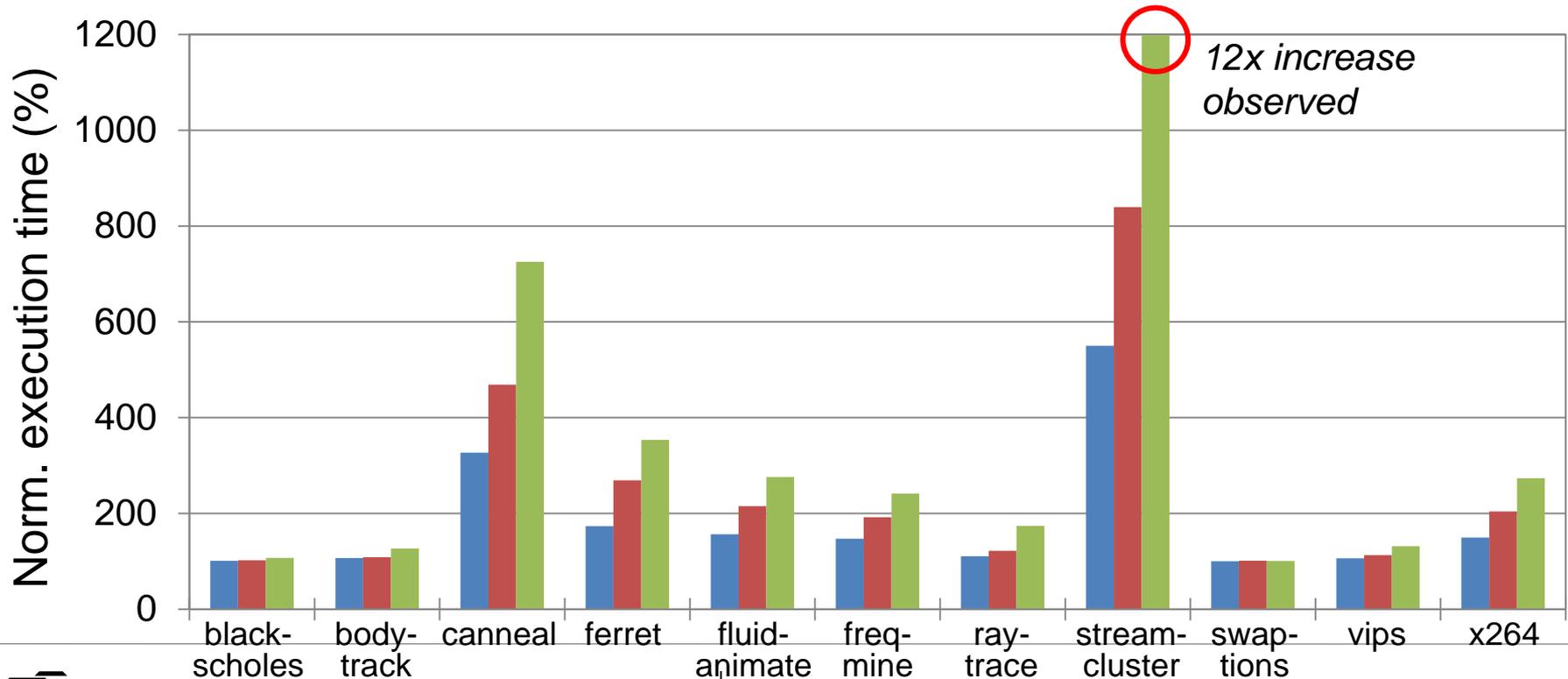
BANK



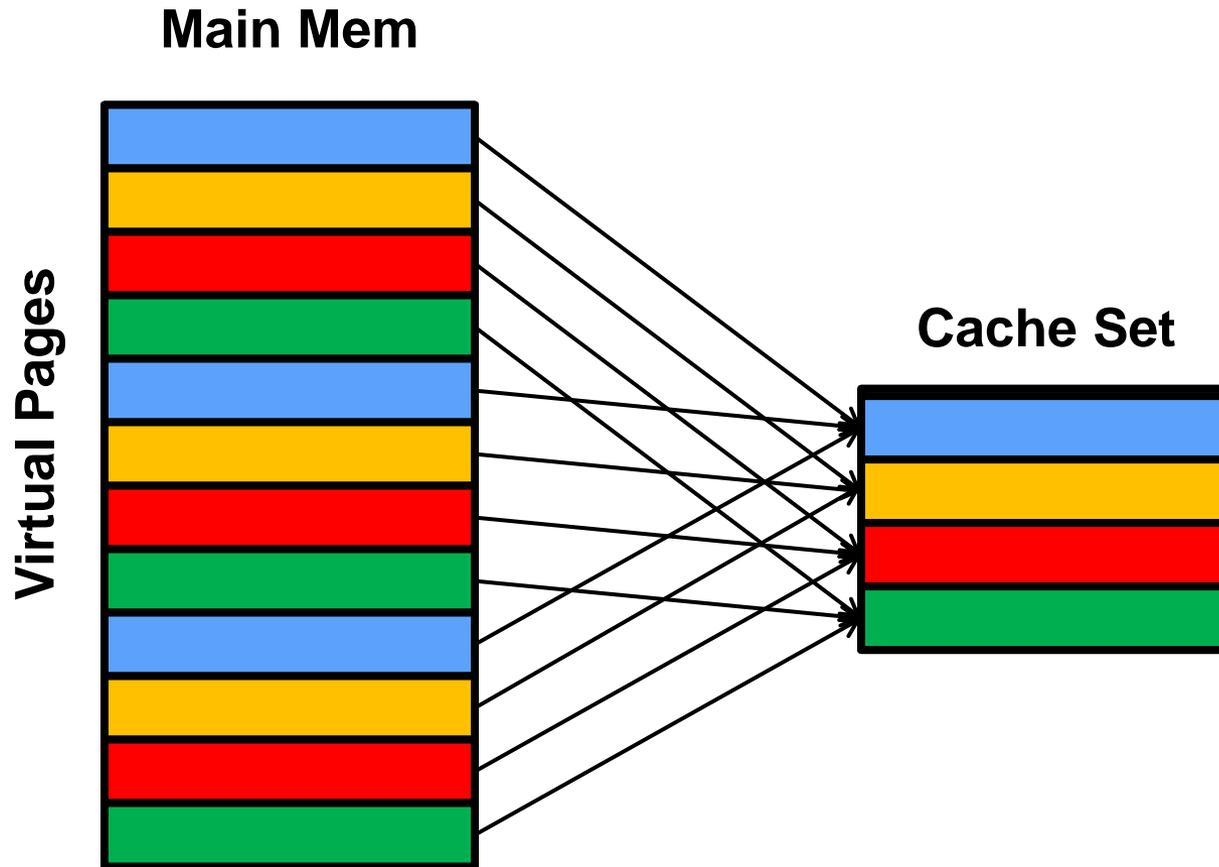
# Impact of Memory Interference

- 1 attacker → Max **5.5x** increase
- 2 attackers → Max **8.4x** increase
- 3 attackers → Max **12x** increase

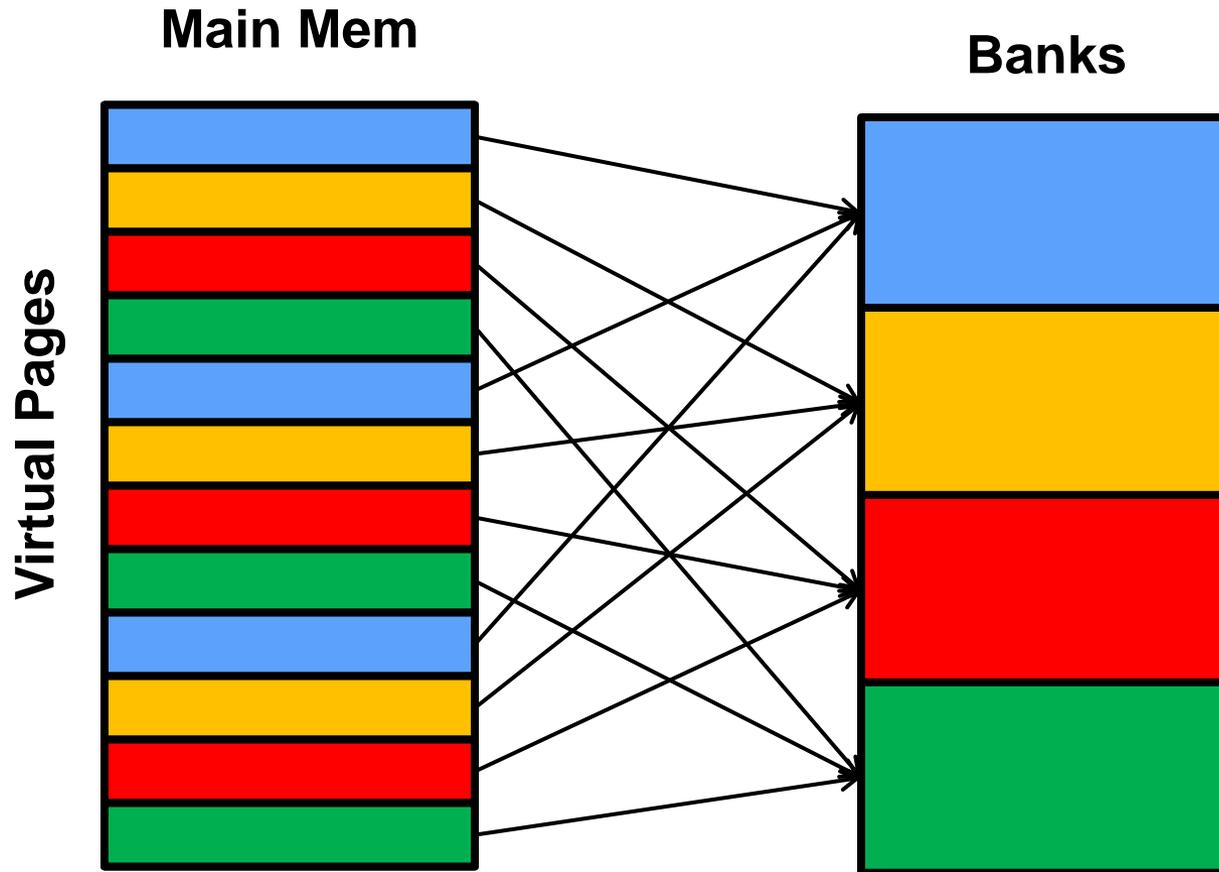
We should *predict*, *bound* and *reduce* the memory interference delay!



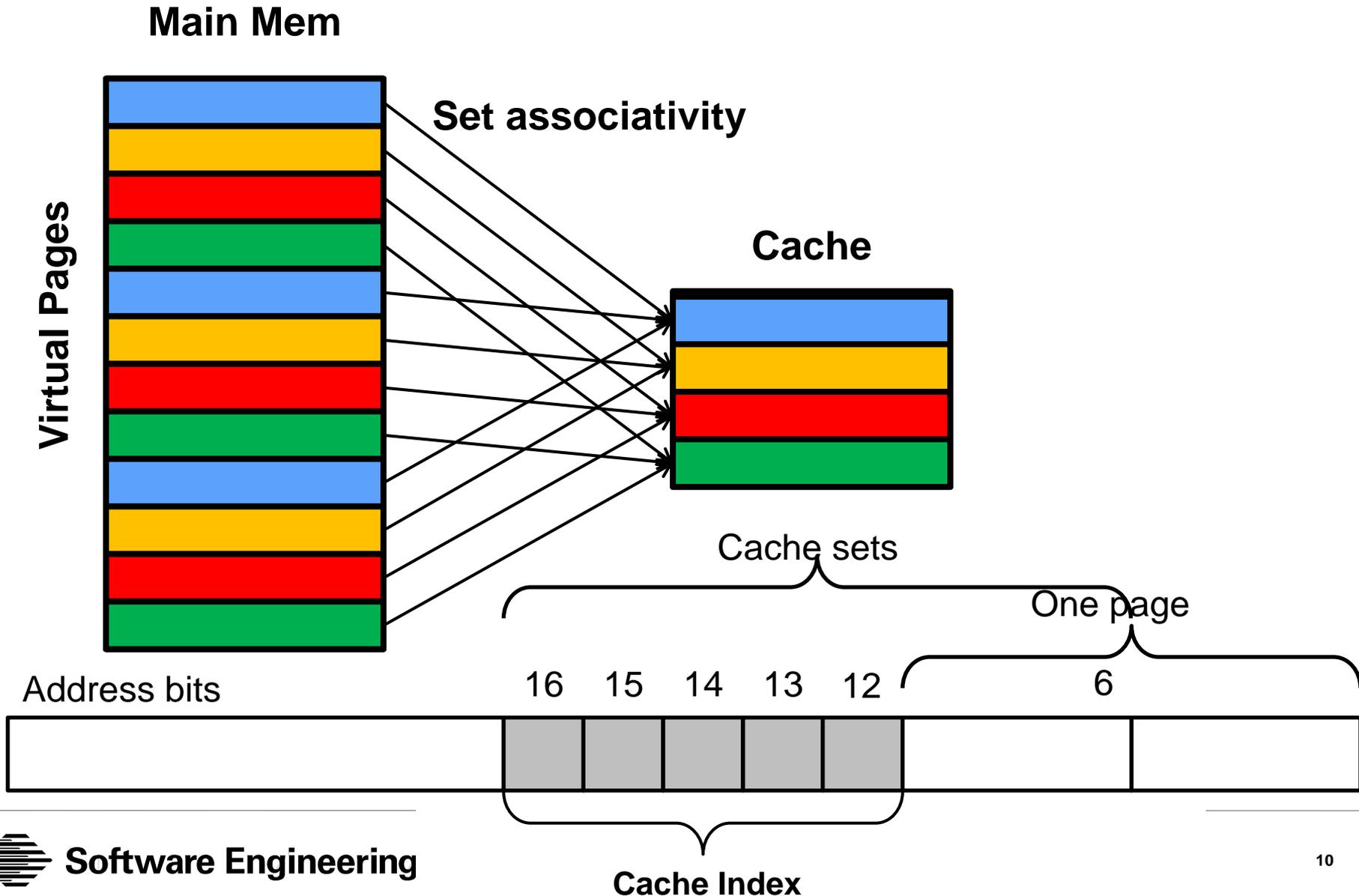
# Cache / Bank Partitioning (Coloring)



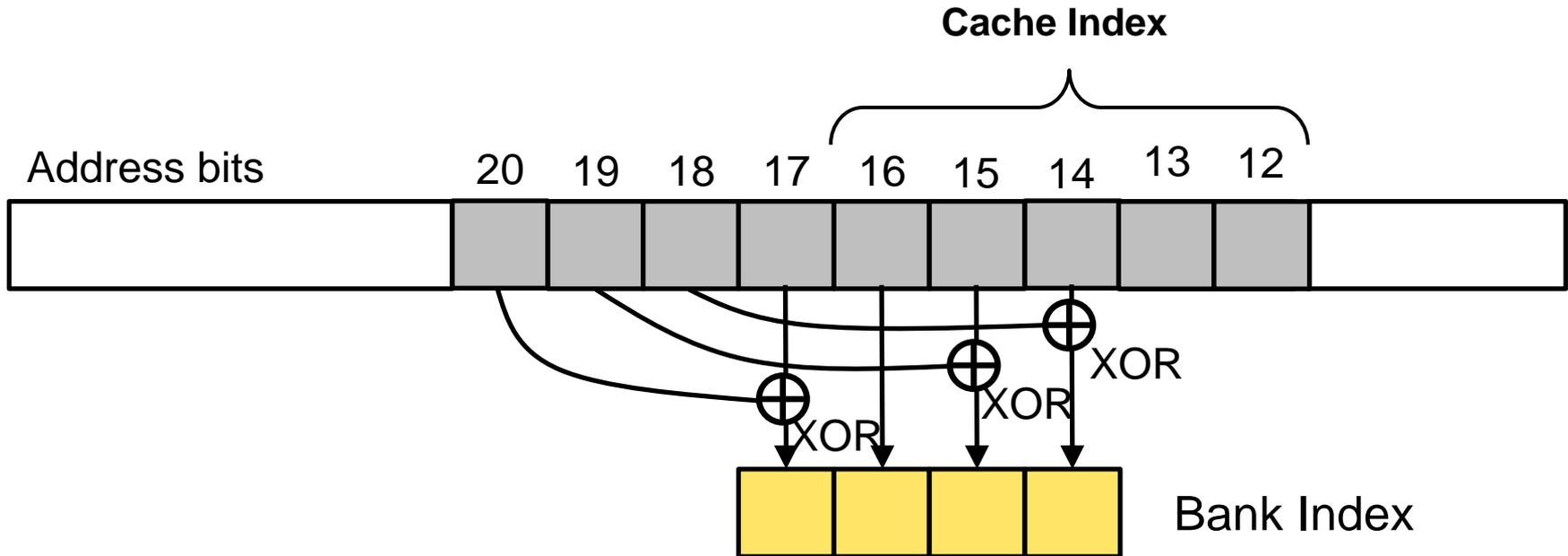
# Cache / Bank Partitioning (Coloring)



# Cache / Bank Partitioning (Coloring)



# Cache and Bank Address Bits



**E.g. 2 bank bits  
2 cache bits  
1 shared bit**

		Bank			
		00	01	10	11
Cache	00	X		X	
	01	X		X	
	10		X		X
	11		X		X



# Coordinated Cache and Bank Partitioning (Private Partitions)

Avoid conflicting color assignments

Take advantage of different conflict behaviors

- Banks can be shared within same core but not across cores
- Cache cannot be shared within or across cores

Take advantage of sensitivity of execution time to cache

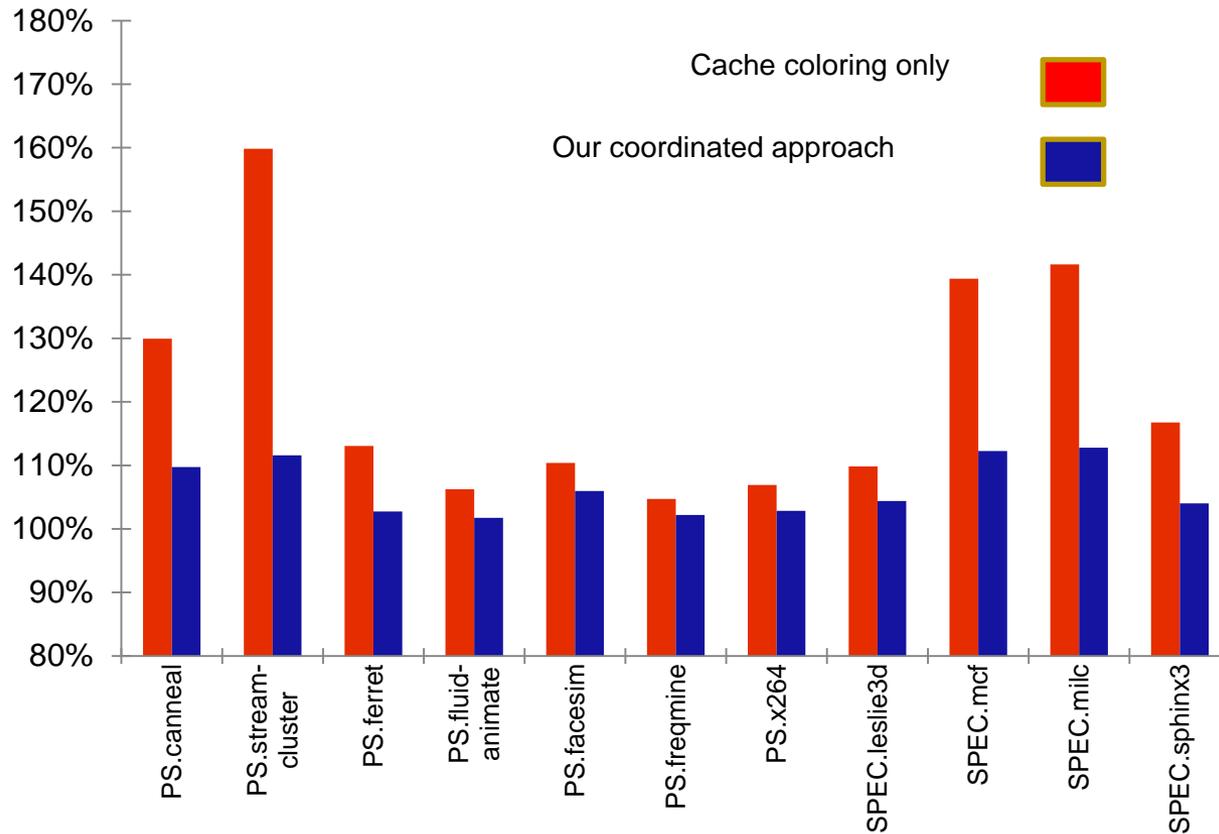
- Task with highest sensitivity to cache is assigned more cache
- Diminishing returns taken into account

Two algorithms explored

- Mixed-Integer Linear Programming
- Knapsack



# Experimental Results



# Shared Bank Partitioning

Explicitly considers the timing characteristics of major DRAM resources

- Rank/bank/bus timing constraints (JEDEC standard)
- Request re-ordering effect

Bounding memory interference delay for a task

- Combines request-driven and job-driven approaches

Task's own memory requests

Interfering memory requests during the job execution

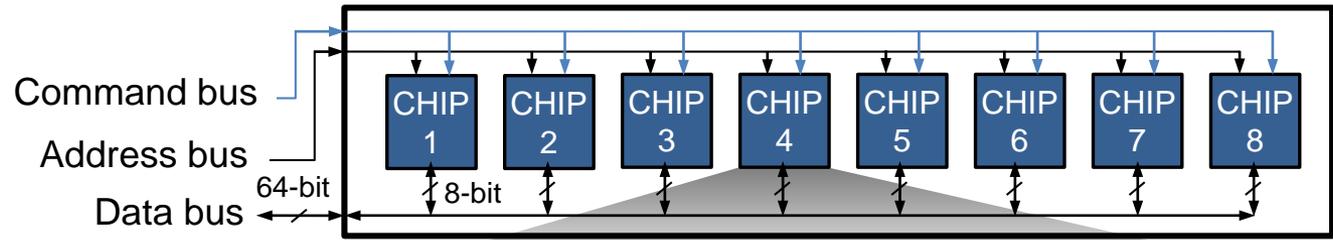
Software **DRAM bank partitioning** awareness

- Analyzes the effect of dedicated and shared DRAM banks

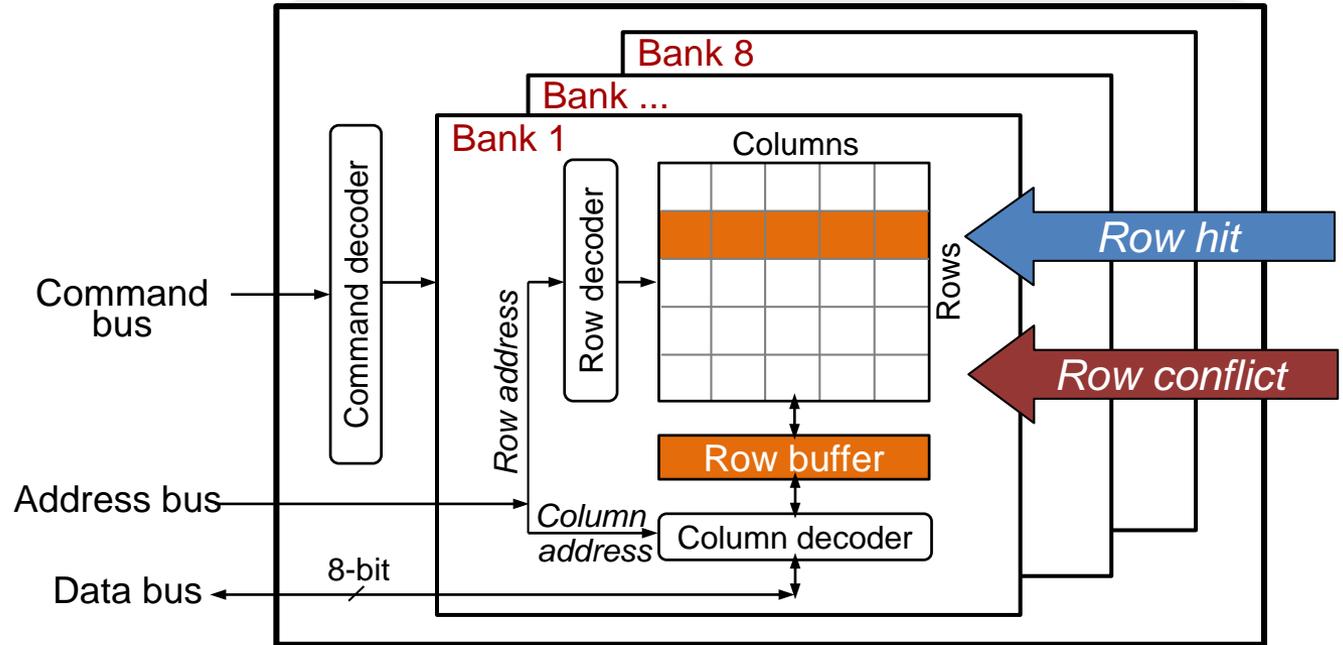


# DRAM Organization

## DRAM Rank



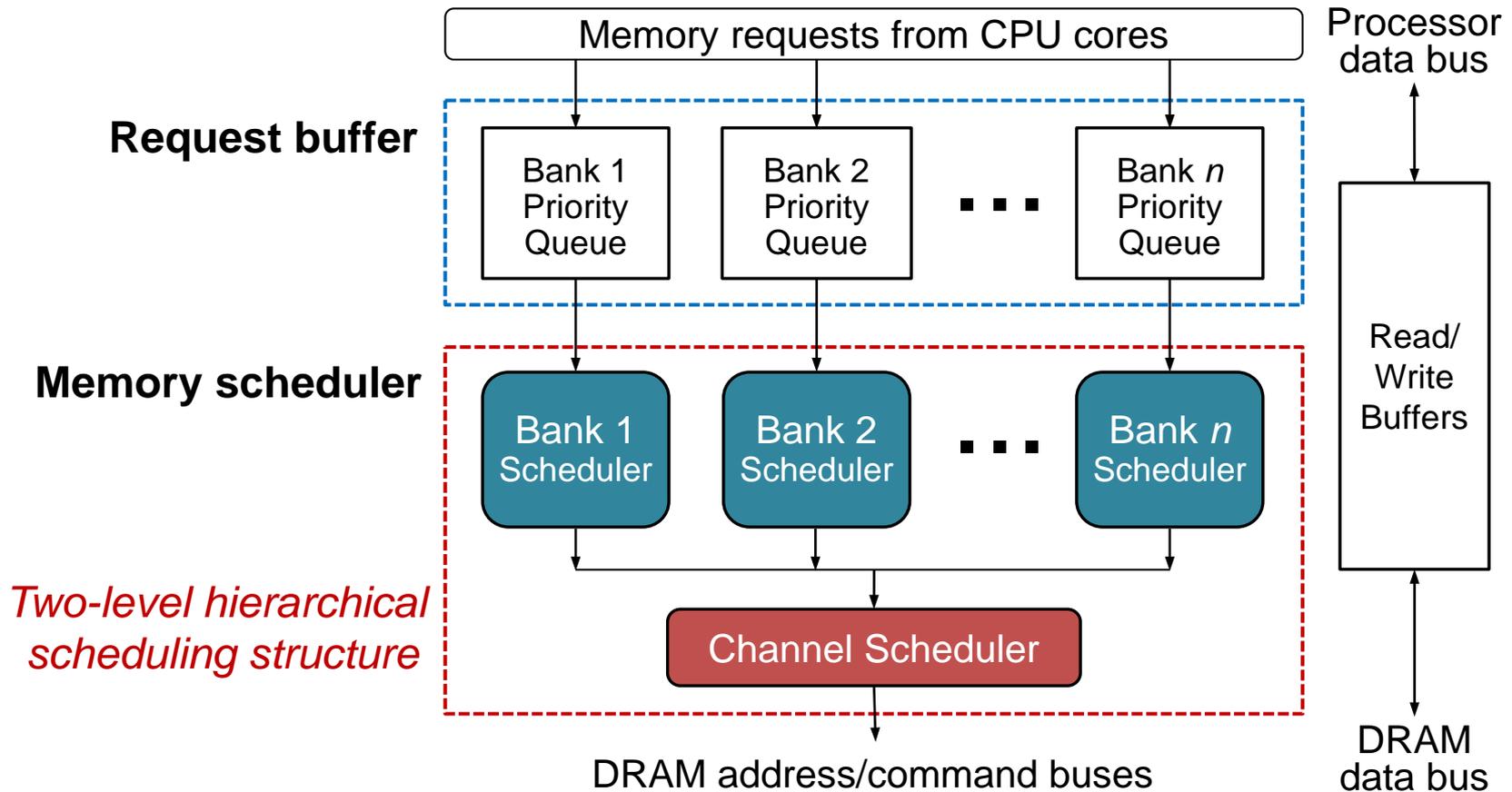
## DRAM Chip



**DRAM access latency** varies depending on which row is stored in the row buffer

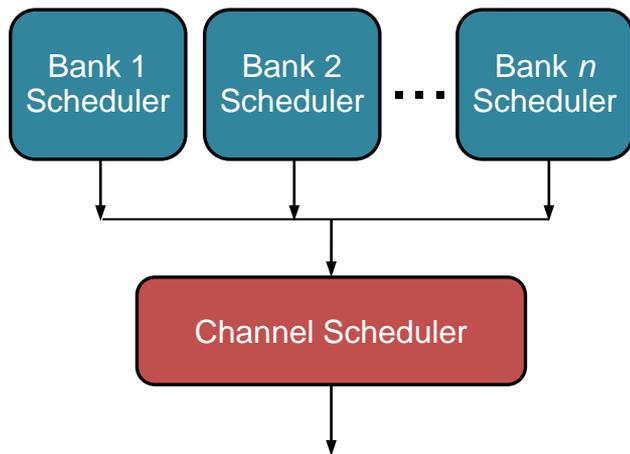


# Memory Controller



# Memory Scheduling Policy

- **FR-FCFS**: First-Ready, First-Come First-Serve
  - Goal: maximize DRAM throughput → Maximize row buffer hit rate



## 1. Bank scheduler

- Considers **bank** timing constraints
- Prioritizes **row-hit** requests
- In case of tie, prioritizes **older** requests

## 2. Channel scheduler

- Considers **channel** timing constraints
- Prioritizes **older** requests

Memory access interference occurs at *both* bank and channel schedulers

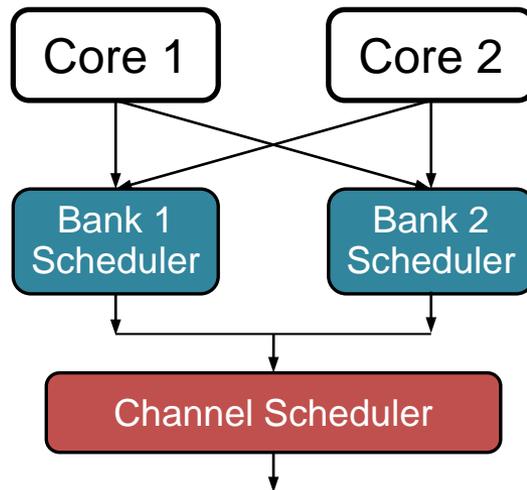
- *Intra-bank interference* at bank scheduler
- *Inter-bank interference* at channel scheduler



# DRAM Bank Partitioning

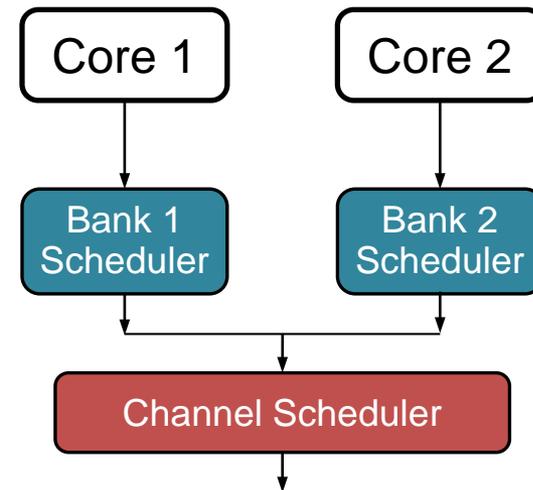
- **Prevents intra-bank interference** by dedicating different DRAM banks to each core
  - Can be supported in the OS kernel

(1) w/o bank partitioning



*Intra-bank and inter-bank interference*

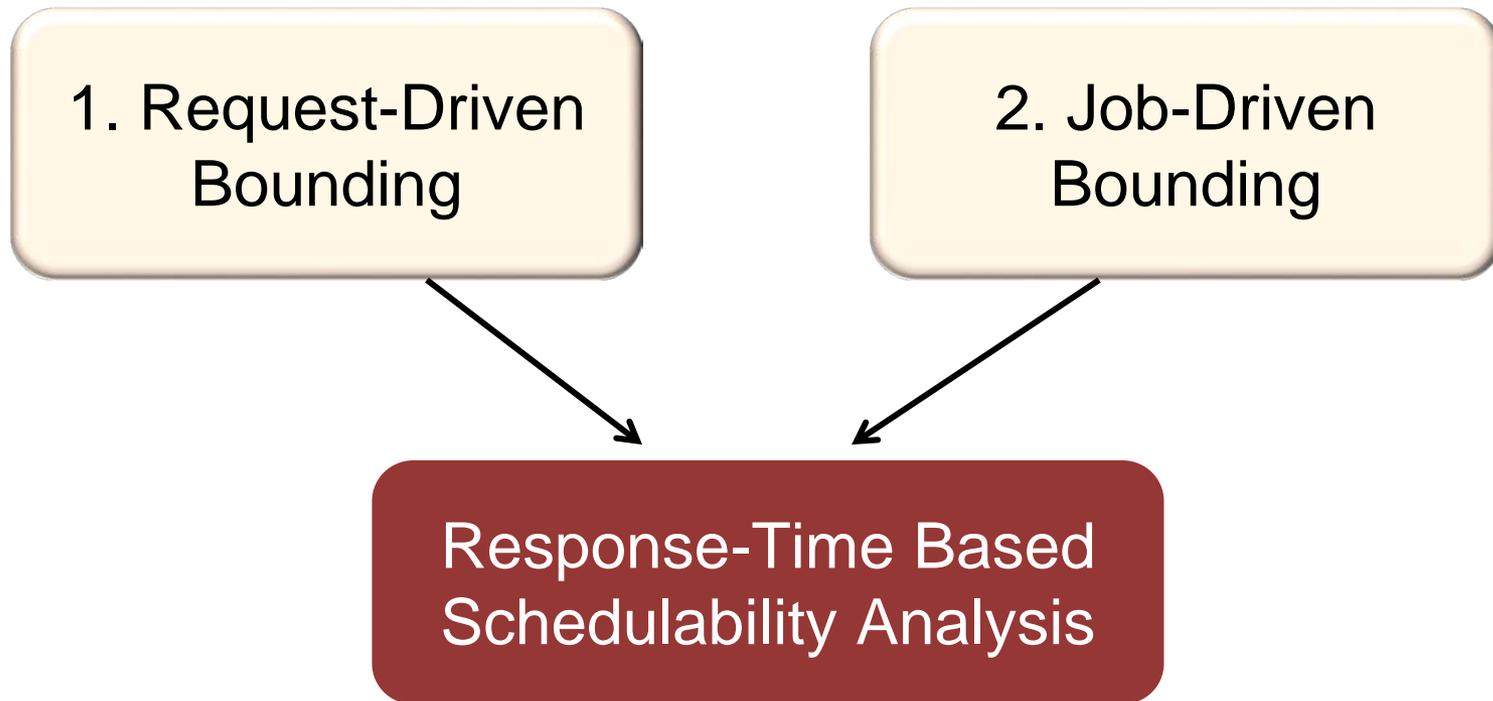
(2) w/ bank partitioning



*Only inter-bank interference*



# Bounding Memory Interference Delay



# Response-Time Test

- **Memory interference delay cannot exceed any results from the RD and JD approaches**
  - We take the smaller result from the two approaches
- **Extended response-time test**

$$R_i^{k+1} = C_i + \sum_{\tau_j \in hp(\tau_i)} \left\lceil \frac{R_i^k}{T_j} \right\rceil \cdot C_j$$

*Classical iterative response-time test*

$$+ \min \left\{ \begin{array}{l} H_i \cdot RD_p + \sum_{\tau_j \in hp(\tau_i)} \left\lceil \frac{R_i^k}{T_j} \right\rceil \cdot H_j \cdot RD_p, \\ JD_p(R_i^k) \end{array} \right\}$$

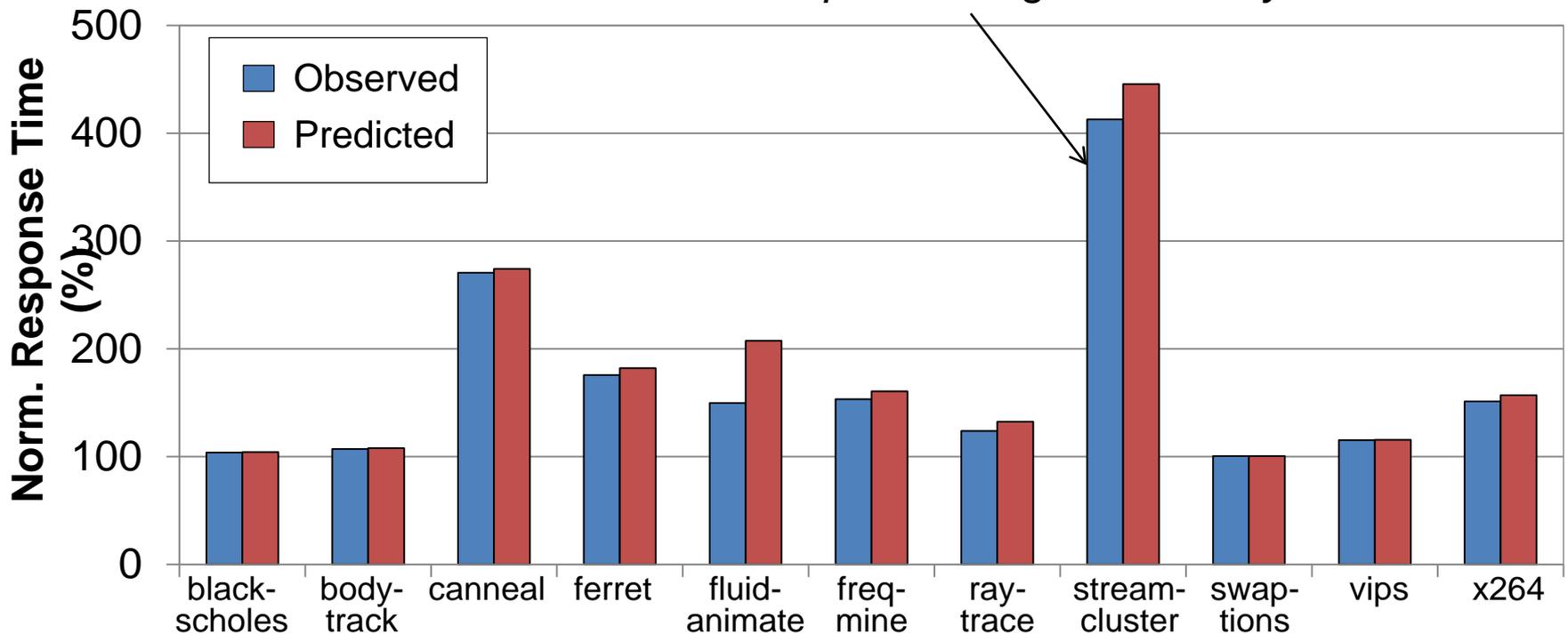
*Request-Driven (RD) Approach*      *Job-Driven (JD) Approach*



# Experiment Severe Memory Interference

- **Private DRAM Bank**

*4.1x increase* → DRAM bank partitioning helps reducing the memory interference

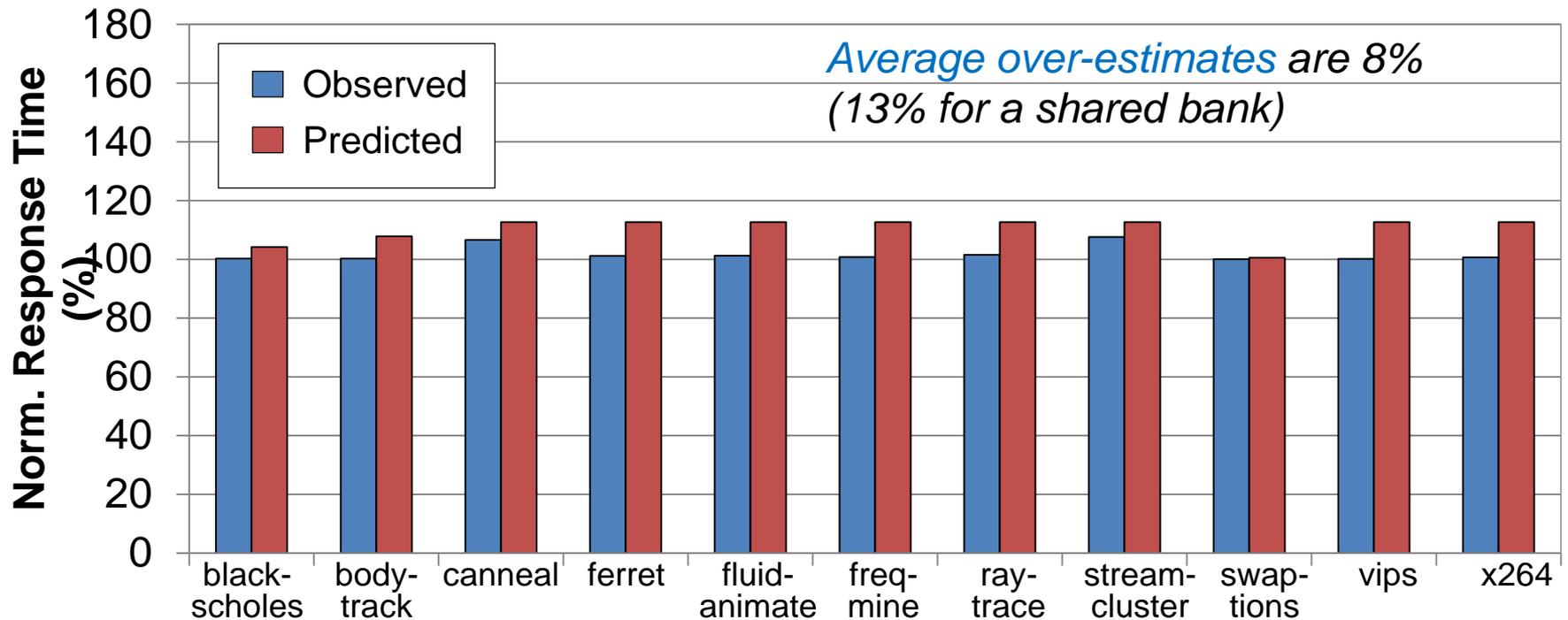


Our analysis enables the **quantification** of the benefit of DRAM bank partitioning



# Non-Severe Memory Interference

- **Private DRAM Bank**



Our analysis bounds memory interference delay with **low pessimism**  
under both **high and low memory contentions**



# Implementation

Cache and Bank Partitioning implemented in Linux/RK

- Associates Resource Reservations to Linux Threads
  - Memory reservation
  - Cache reservation
  - CPU reservation
  - ...

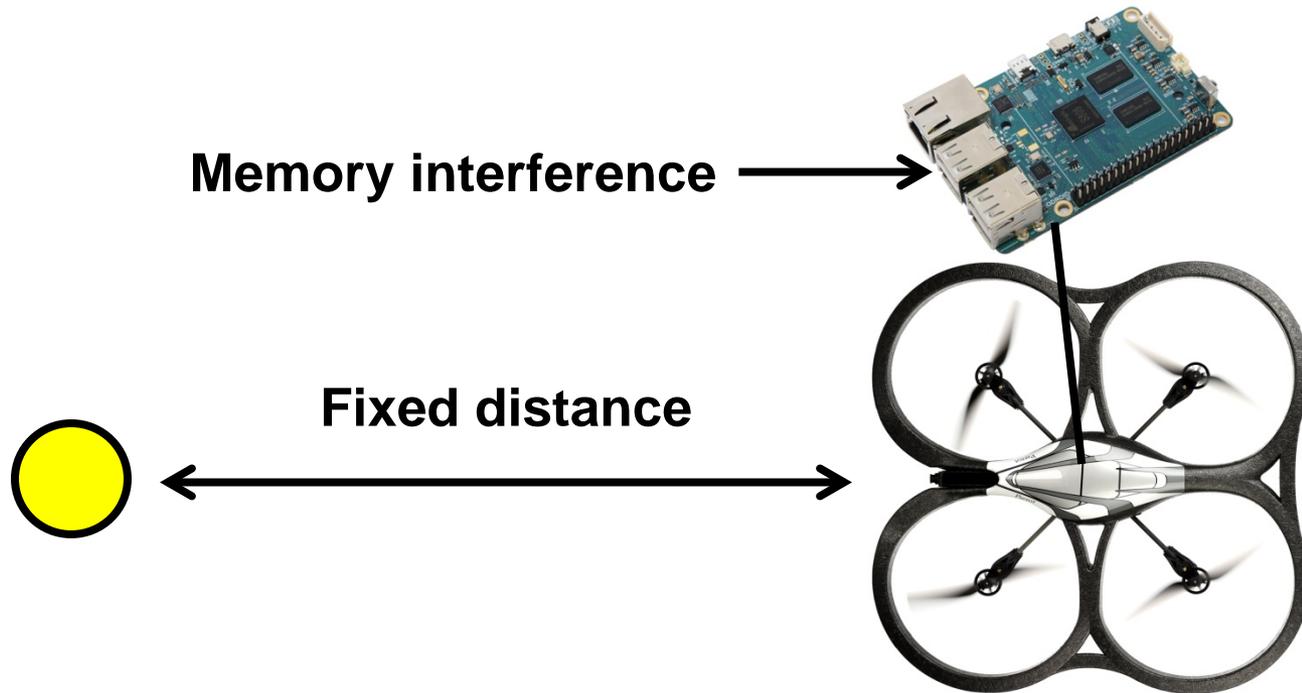
“Portable” Kernel Module

- Hooks into on-demand page allocation
- At boot time create large memory reserve
  - Pages are classified in cache and bank colors



# Model Problem

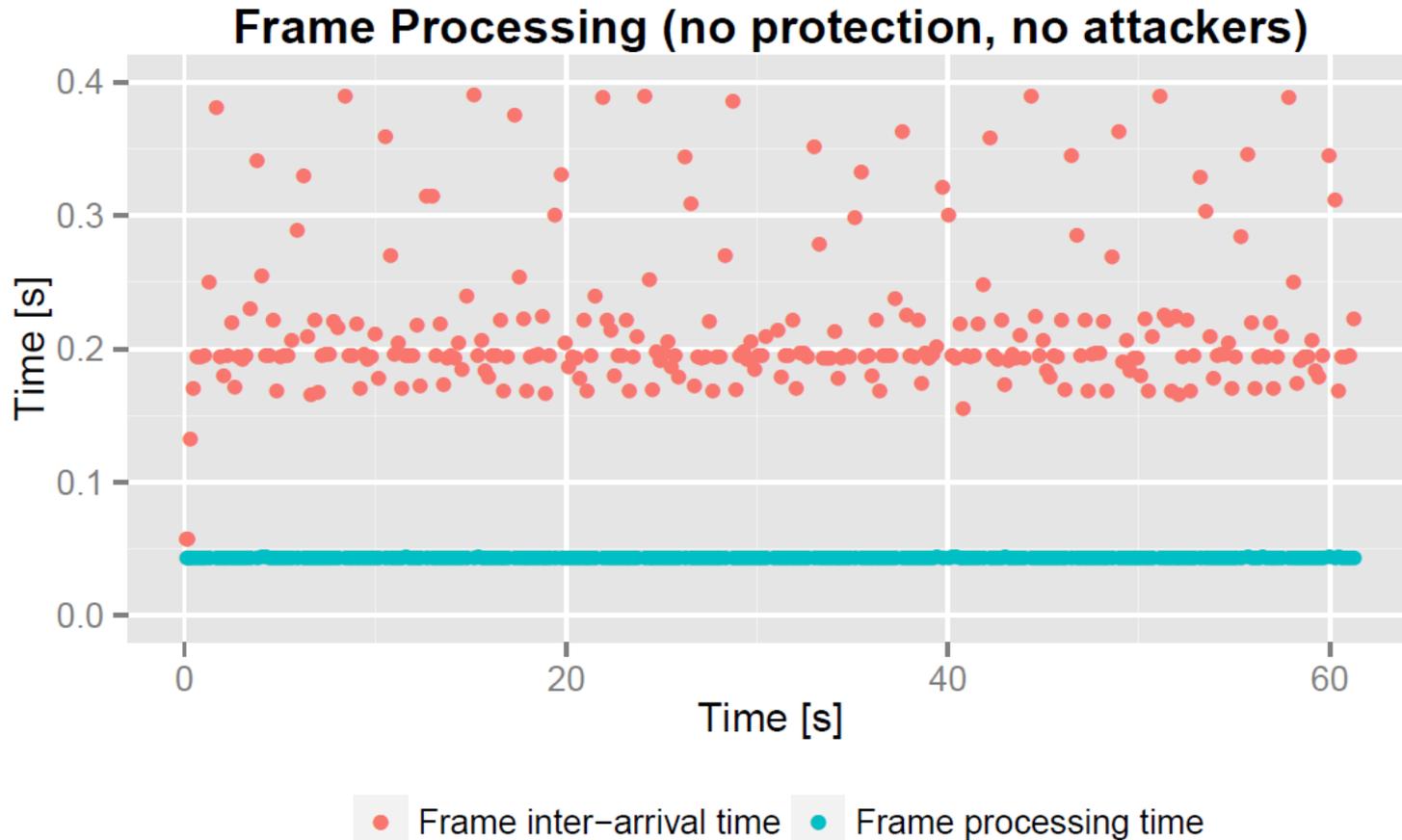
Ball-following Controller  
on Odroid+Linux/RK



**Ball-Following: Keep fixed distance as  
ball moves around**

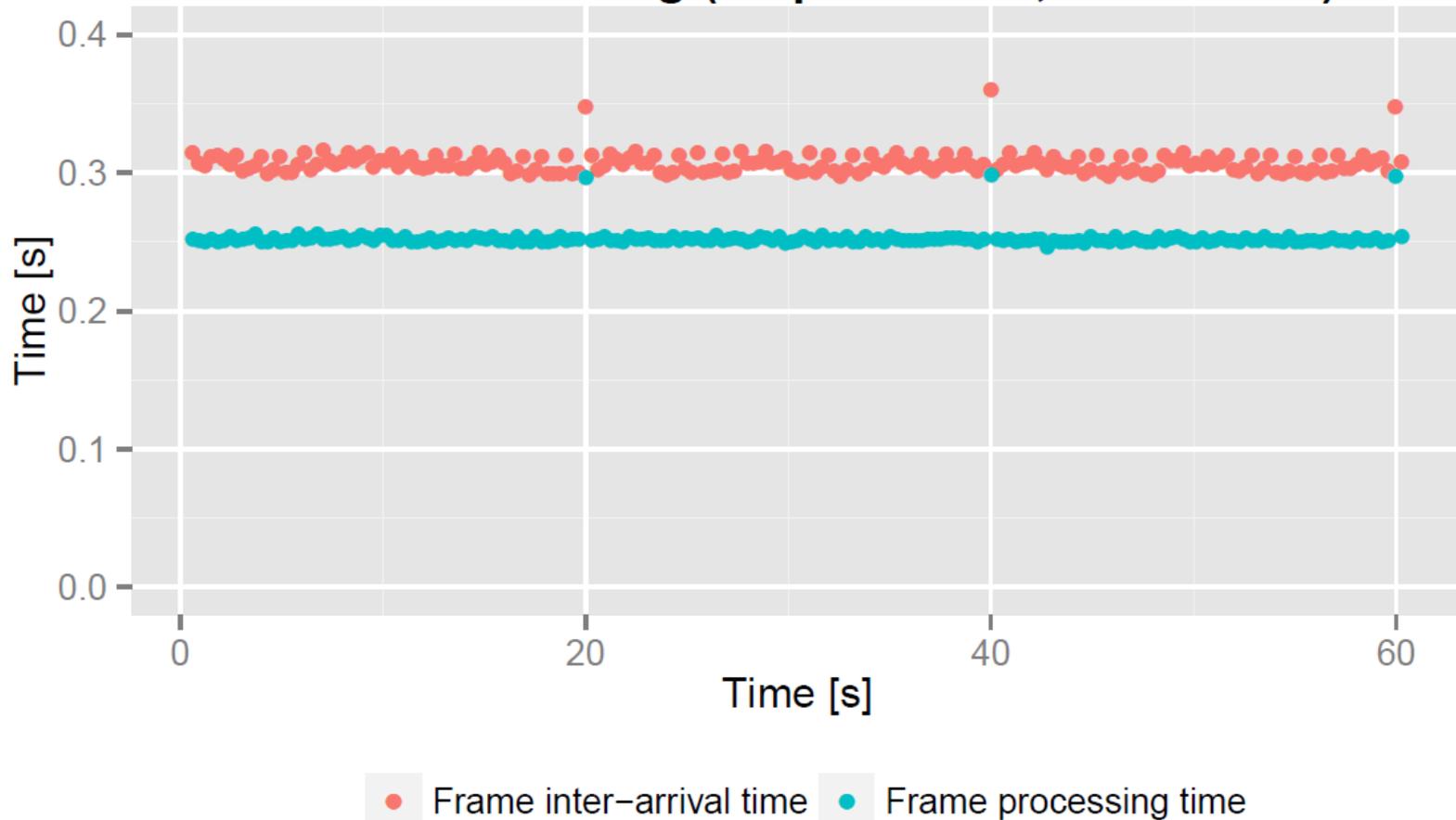


# Experimental Results (1)



# Experimental Results (2)

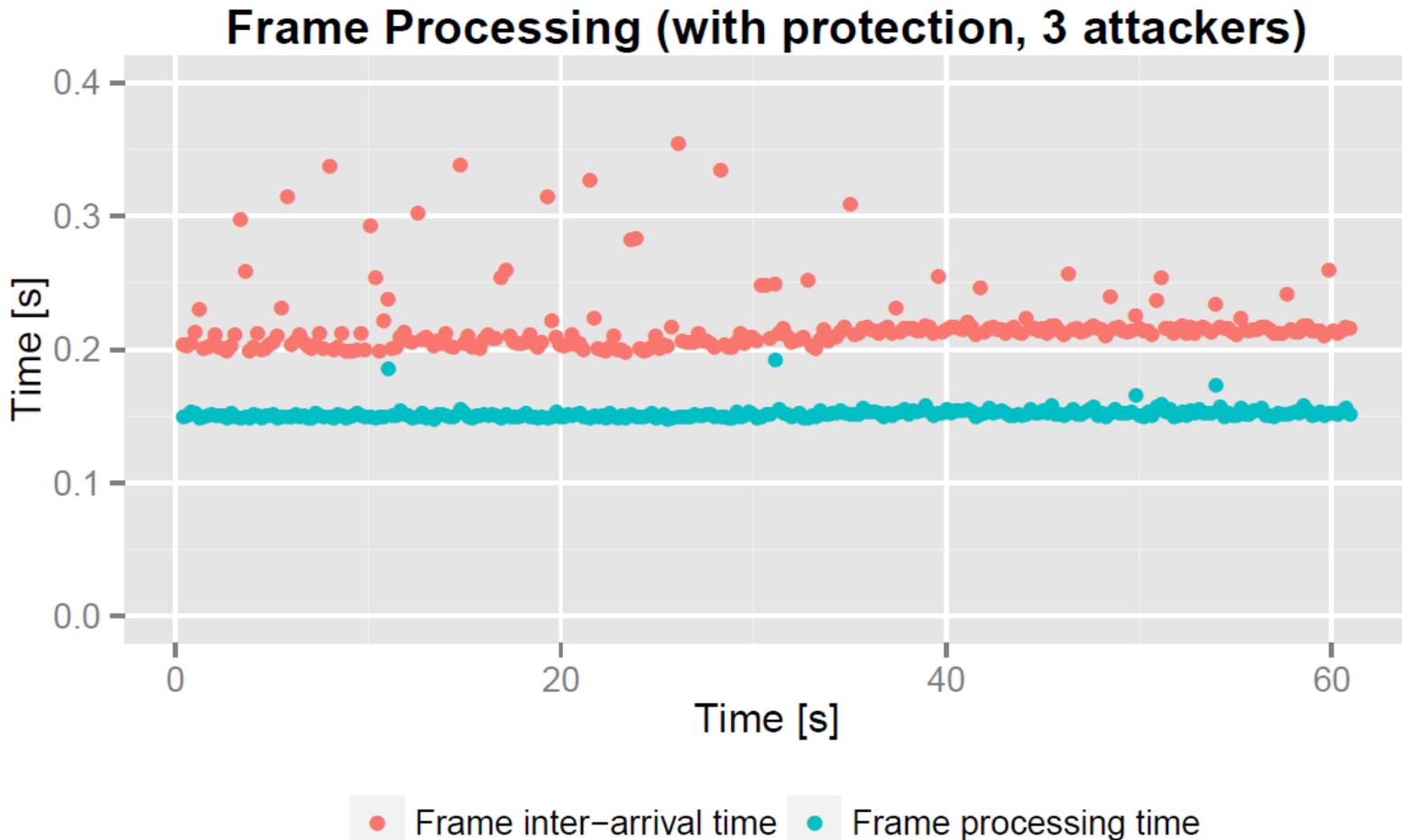
## Frame Processing (no protection, 3 attackers)



**Deadlines misses at 0.2. only 195 out of 279 frames processed (30% loss)**



# Experimental Results (3)



**No deadline misses. Processing below 0.2 s interarrival (period)**



# Concluding Remarks

Multicore processor challenges previous results in real-time systems

- Interference from shared hardware
  - Cache, Memory banks, Memory bus

Leads to less usable processing capacity

- 1200% increase in a four core machine (92% reduction from single core)

Our approach

- Coordinated private partitions for cache and memory
- Shared bank partitions
- Implemented in Linux/RK

Experimental results for model avionics application

- Protects control algorithm from interference

