Cornell University
Computer Systems Laboratory

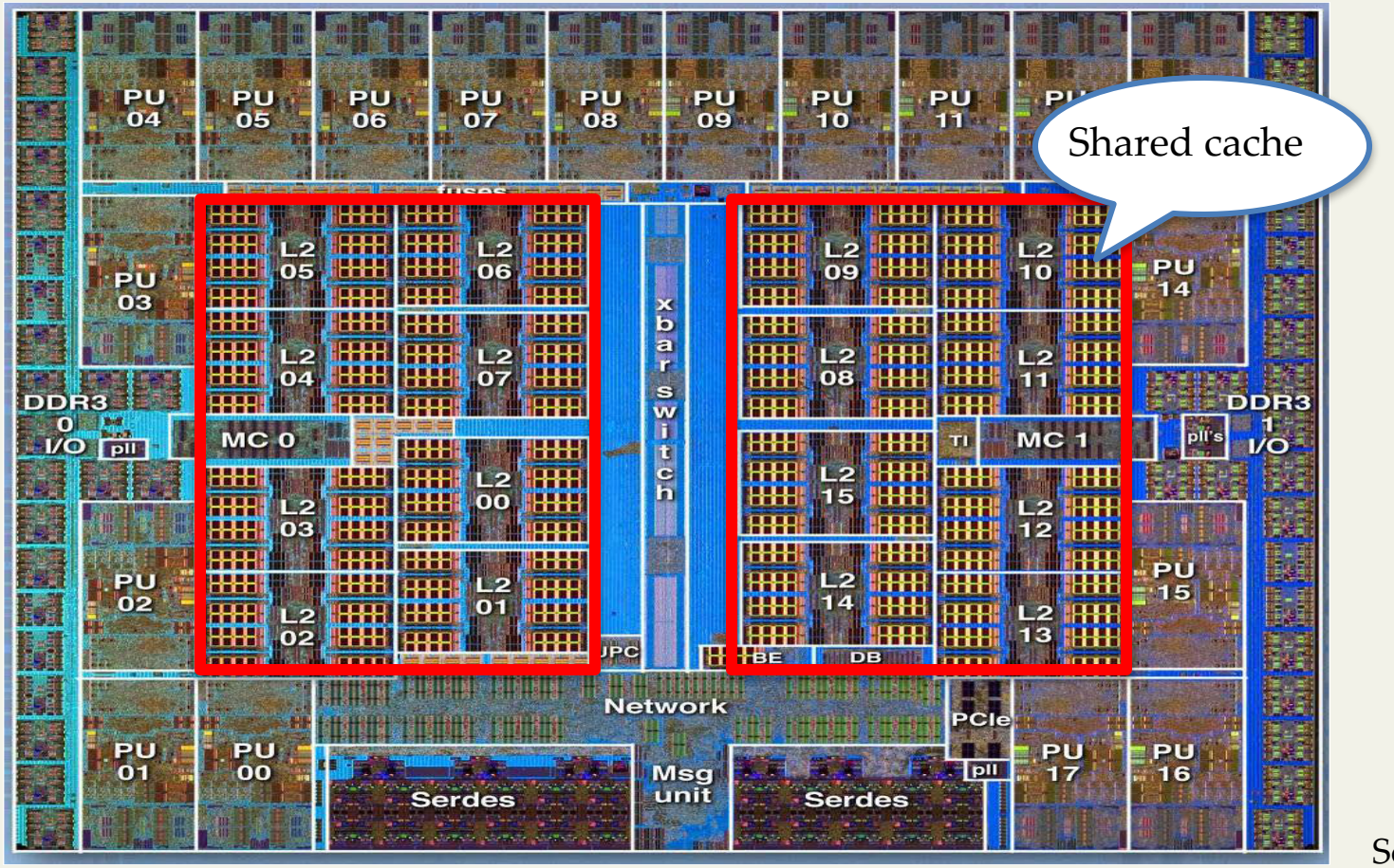
SWAP: EFFECTIVE FINE-GRAIN MANAGEMENT OF SHARED LAST-LEVEL CACHES WITH MINIMUM HARDWARE SUPPORT

Xiaodong Wang, Shuang Chen, Jeff Setter,
and José F. Martínez

Computer Systems Lab
Cornell University

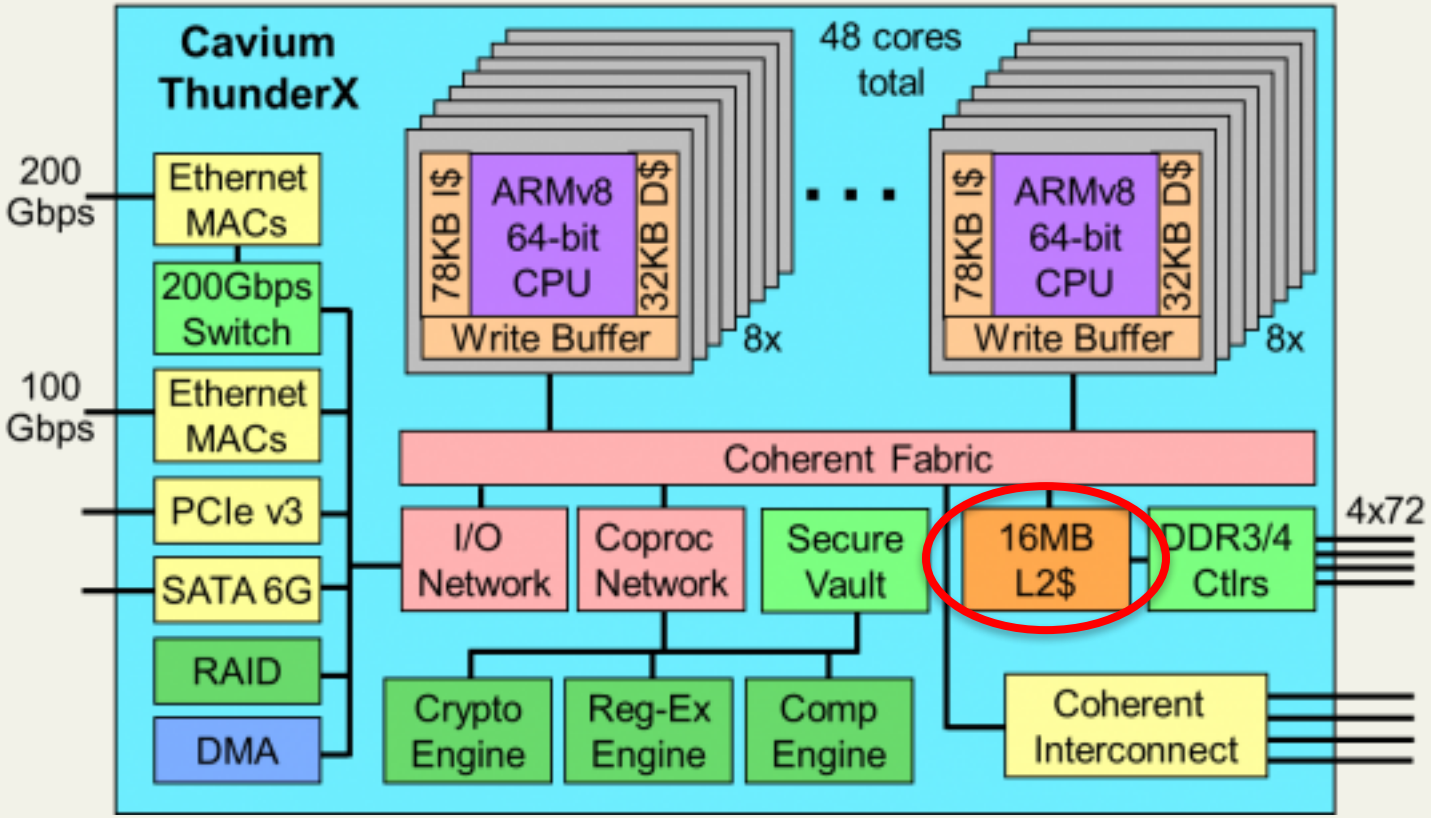
Cornell University
Computer Systems Laboratory

- IBM Blue Gene/Q



Source: IBM

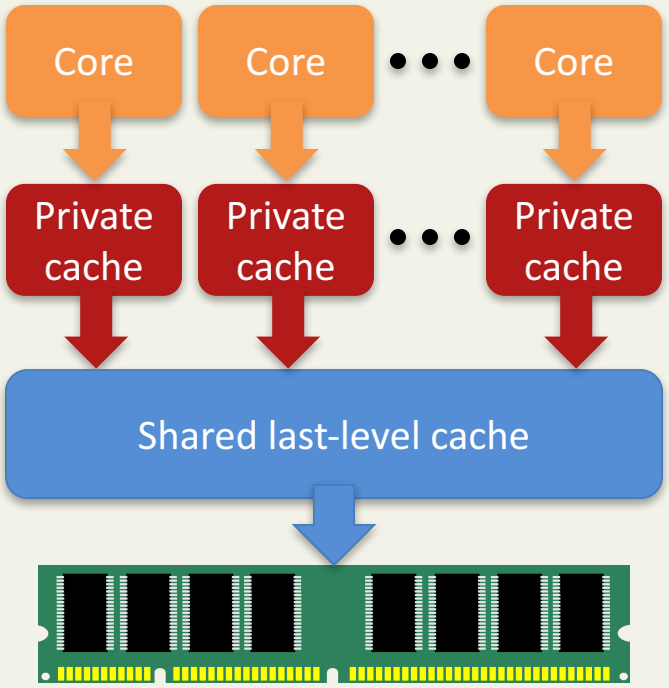
- Cavium ThunderX® 48-core CMP



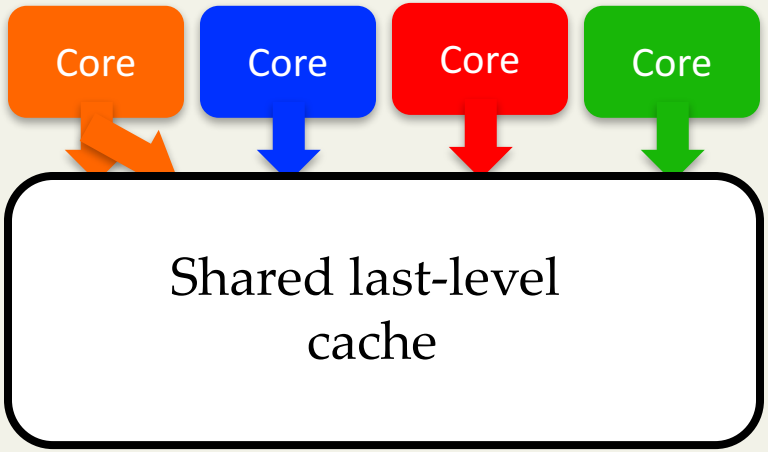
Source: Cavium

Motivation

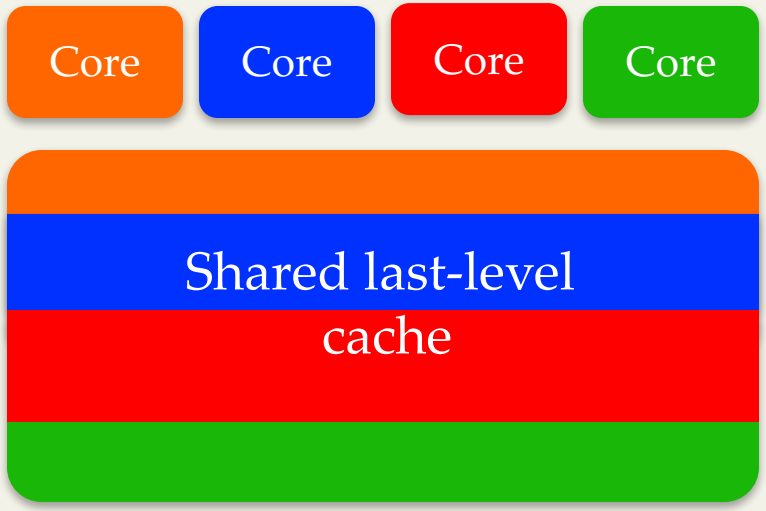
- **Last-level cache is critical to system performance**
  - ~50% chip area
- **Performance isolation in shared cache**
  - Improve system throughput
  - Guarantee QoS of latency-critical workloads
  - Eliminate timing channels



- **Cache way partition**
  - Assign different cache ways to different cores
  - Coarse-grained
    - 16 cache ways in ThunderX 48-core processor
  - Associativity lost

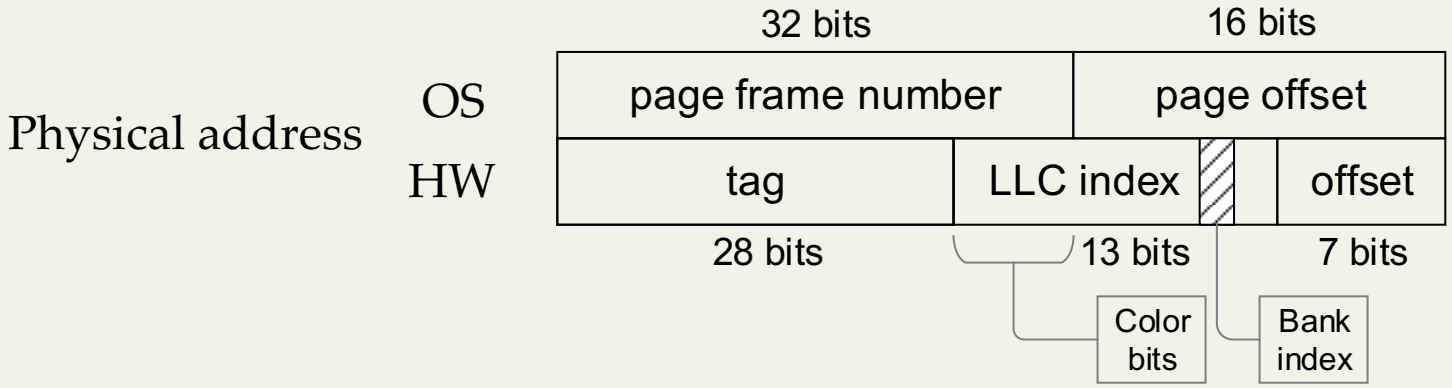


- **Page coloring**
  - Assign different cache sets to different cores
  - Perfect isolation
  - OS-level software technique



- **Page coloring**
  - Assign different cache sets to different cores
  - Perfect isolation

- High repartition overhead
- Coarse-grained: the number of page colors is limited
  - 4 color bits, 16 colors in ThunderX 48-core processor



- **Fine-grained cache partitioning [1, 2, 3, 4]**
  - Probabilistically guarantee the size of partitions at the granularity of cache lines
  - Requires non-trivial hardware changes
  - No clear boundary across partitions: isolation is not strict

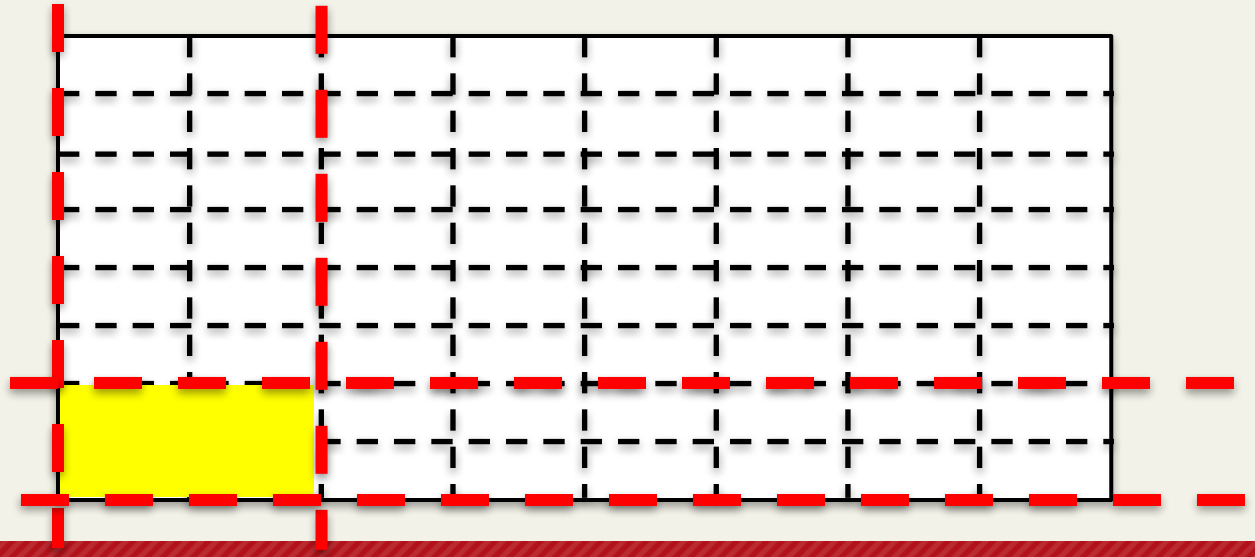
[1] Xie and Loh, ISCA' 09
[2] Sanchez and Kozyrakis, ISCA' 11
[3] Manikantan et al., ISCA' 12
[4] Wang and Chen, MICRO' 14

Comparison of schemes

	Way partitioning	Page coloring	Probabilistic partitioning	SWAP
Perfect isolation	Yes	Yes	Probabilistic	Yes
Fine-grain	No	No	Yes	Yes
Hardware overhead	Low	No	High	Low
Real system	Yes	Yes	No	Yes
Repartition overhead	Low	High	Low	Median

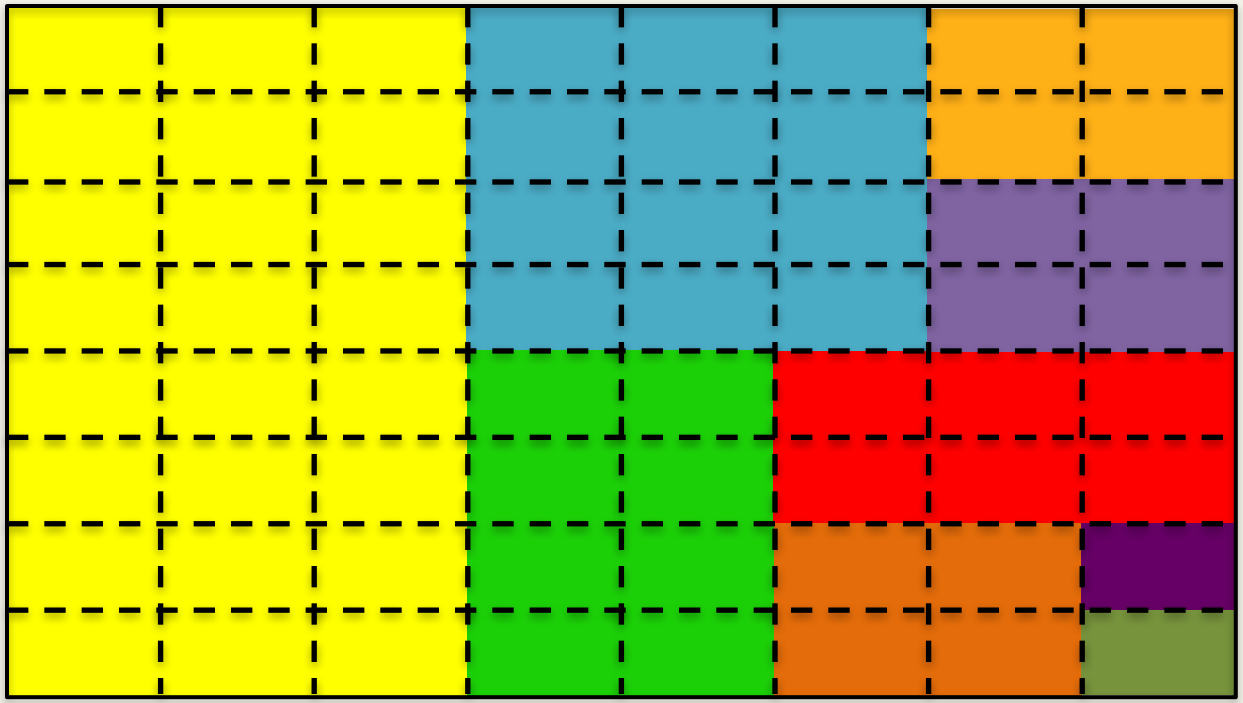
SWAP: Set and Way Partitioning

- **Way partitioning vertically divides the cache**
  - 16 cache ways in ThunderX for 48 cores
- **Page coloring horizontally divides the cache**
  - 16 page colors in ThunderX for 48 cores
- **Combine way partitioning and page coloring**



SWAP: Set and Way Partitioning

- **Combine way partitioning and page coloring**
  - Divide the cache in a 2-dimensional manner
  - Maximum 256 partitions w/ 16 cache ways and 16 page colors, fine-grained enough for 48 cores



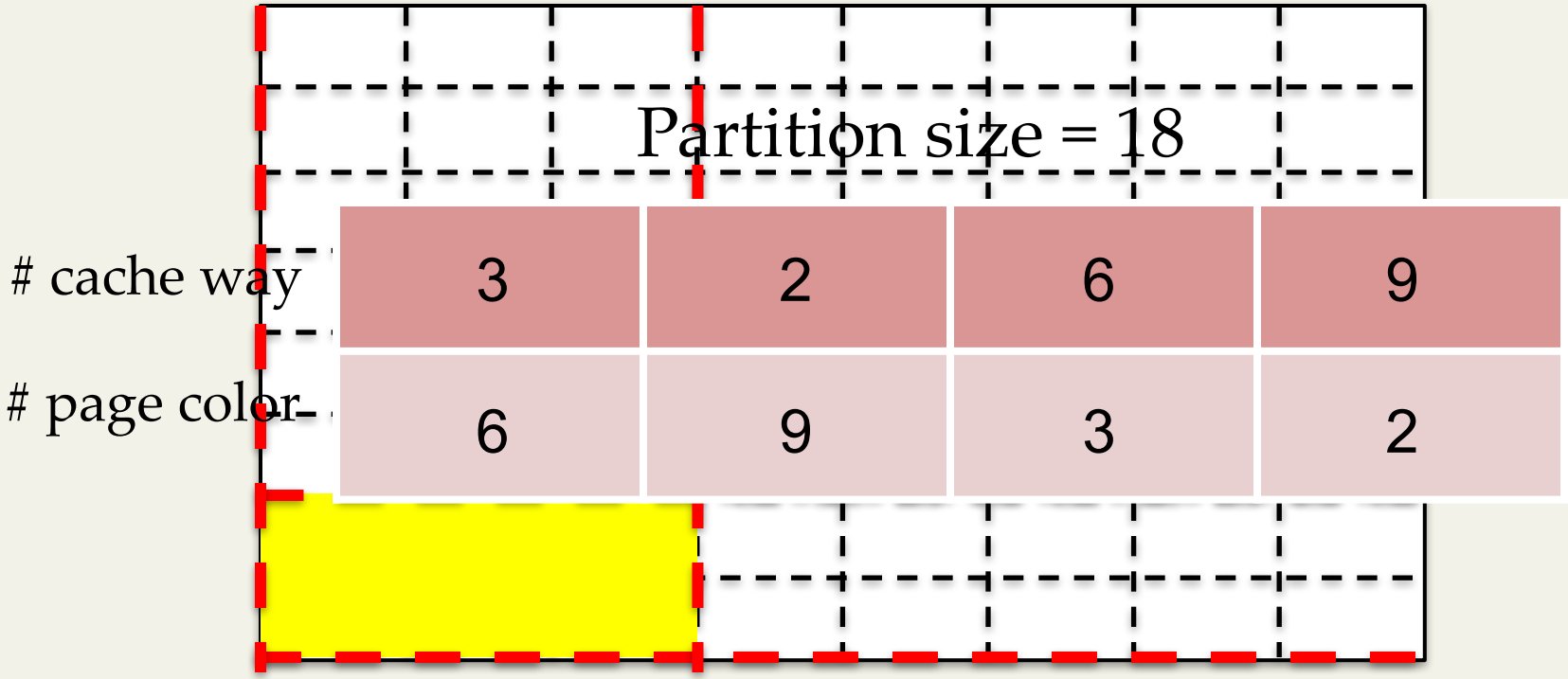
SWAP: Set and Way Partitioning

- **Contribution**
  - Combine way partitioning and page coloring that enables fine-grain cache partition in real systems

- **Challenges**
  - What's the shape of the partition?
  - How are partitions placed with each other?
  - How to minimize repartition overhead?

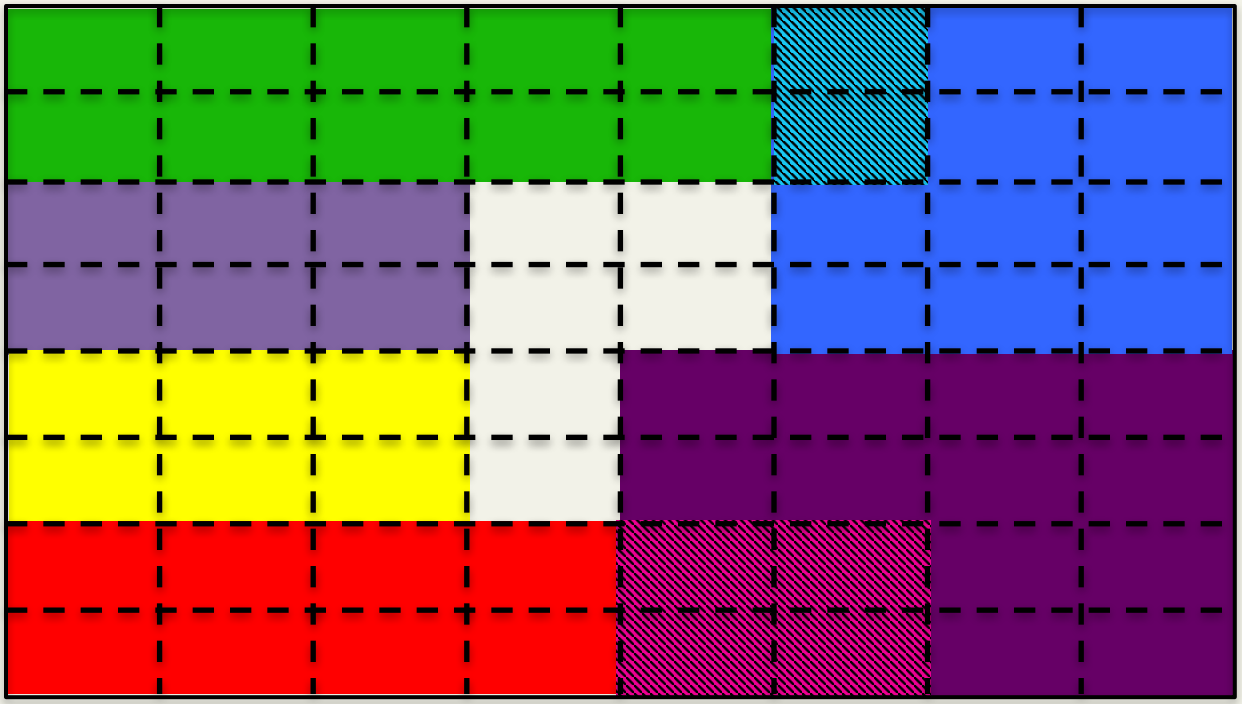
SWAP: Set and Way Partitioning

- **Partition shape**
  - Given the partition size, how many cache ways and pages colors should the partition have?



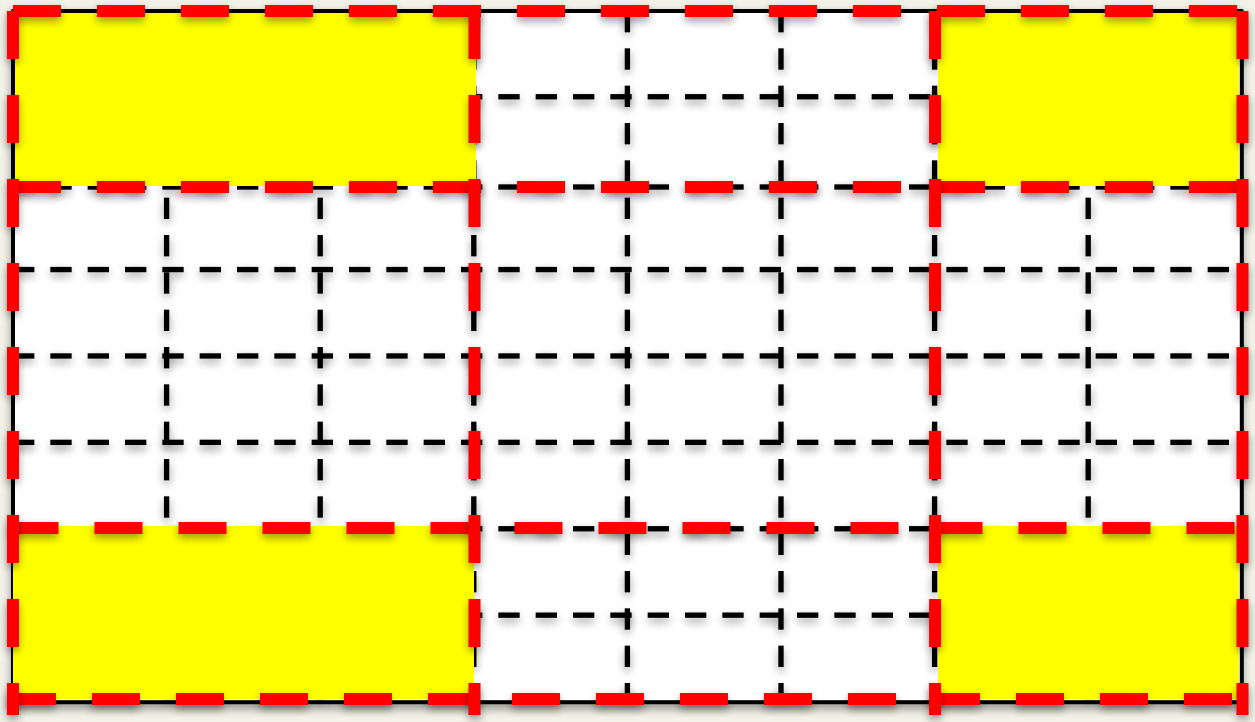
SWAP: Set and Way Partitioning

- **Partition Placement**
  - Partitions do not overlap (interference-free)
  - No cache space is wasted



SWAP: Set and Way Partitioning

- **Partition shape**
  - Partitions cannot simply expand to occupy unused area



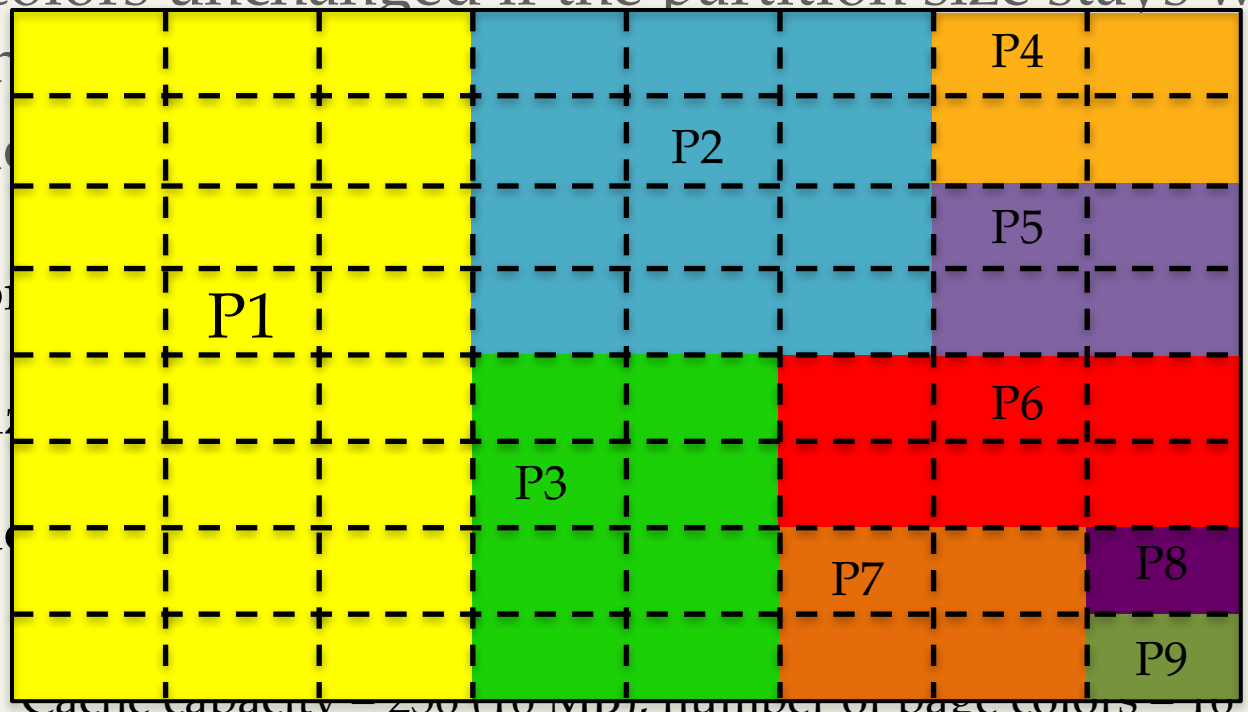
SWAP: Set and Way Partitioning

- **Partition shape**
  - Given the partition size, we classify the partitions into different categories
  - Page colors unchanged if the partition size stays within a certain
  - Partiti

Categor

Partition si

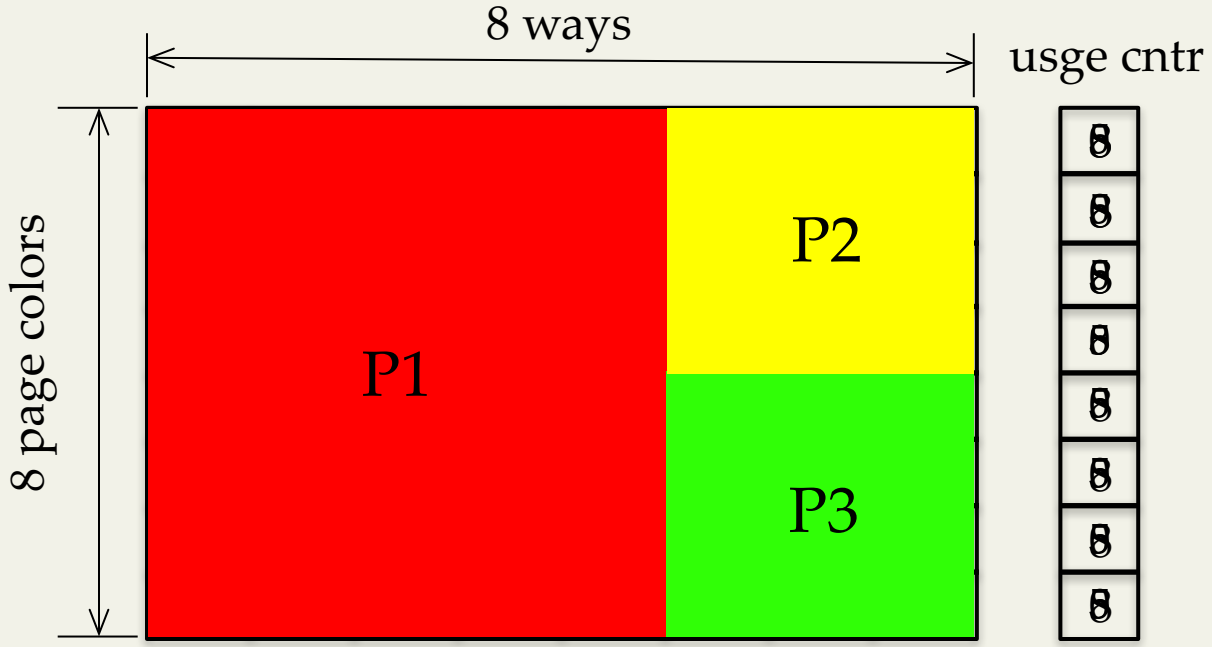
page col



Cache capacity = 256 (16 MB), number of page colors = 16

- **Partition Placement**
  - Start with large partitions (with more colors)
  - Assign the partition with page colors that have most cache ways left

	Size
P1	40
P2	12
P3	12



SWAP: Set and WAy Partitioning

- **Reduce repartition overhead**
  - Adjust cache way assignment incurs low overhead
    - » Write way permission register
  - Adjust page color assignment is cumbersome
    - » Migrate the page from the old color to the new color

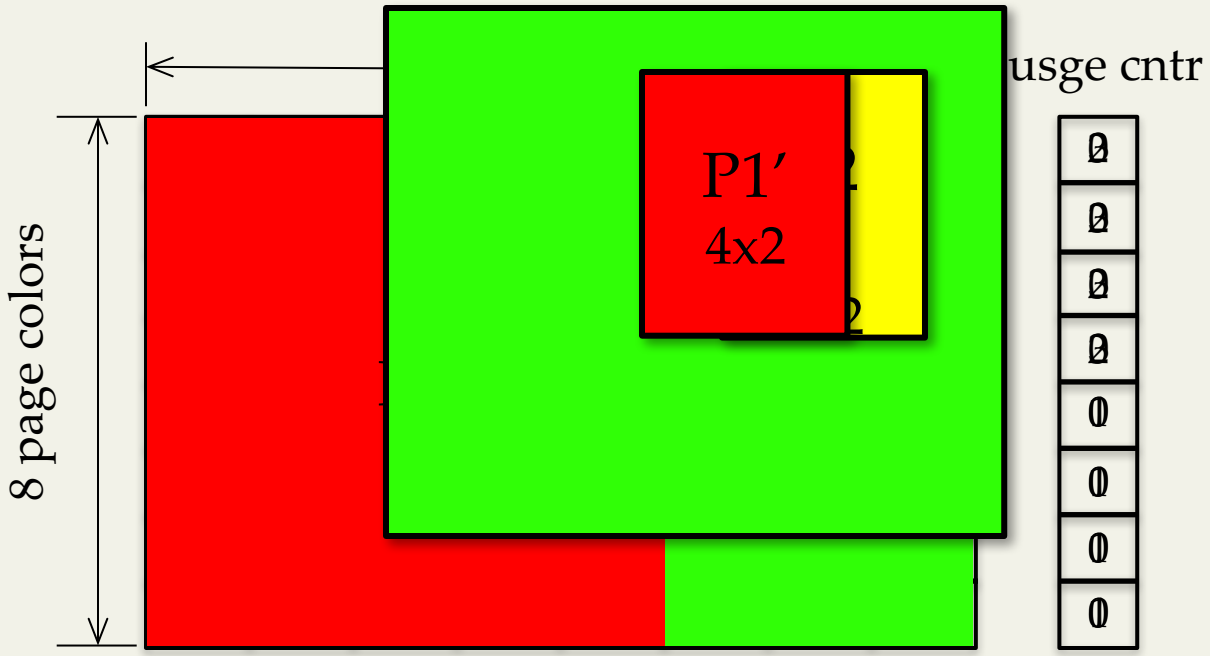
SWAP: Set and Way Partitioning

- **Reduce repartition overhead**
  - Key: reduce page re-coloring
  - Classify the partitions as before
    - » Same: keep the original colors
    - » Downgrade: use partial original colors
    - » Upgrade: may use any colors
  - Estimate the cache way usage before placement

SWAP: Set and Way Partitioning

- **Reduce repartition overhead**
  - Classify the partitions as before
  - Estimate the cache way usage

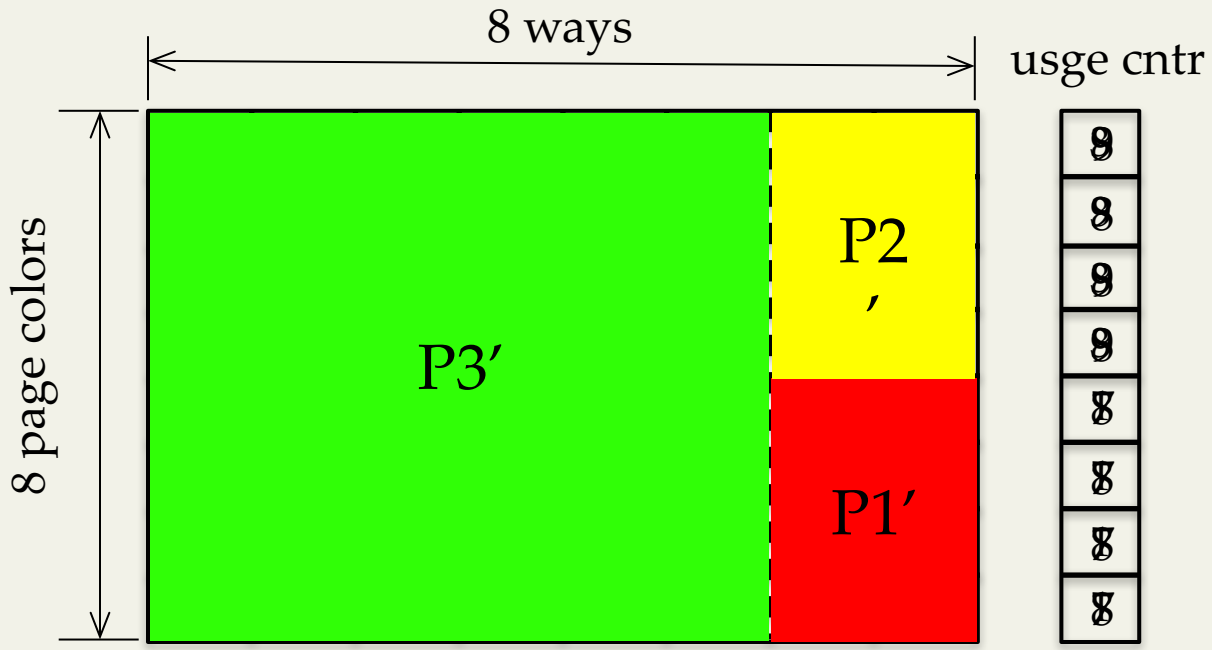
	Before	After	
P1	40	8	Down
P2	12	8	
P3	12	48	Up



SWAP: Set and Way Partitioning

- **Reduce repartition overhead**
  - Start with large partitions (with more colors)
  - Assign the partition with page colors that have most cache ways left

	Before	After	
P1	40	8	Down
P2	12	8	
P3	12	48	Up



Other issues

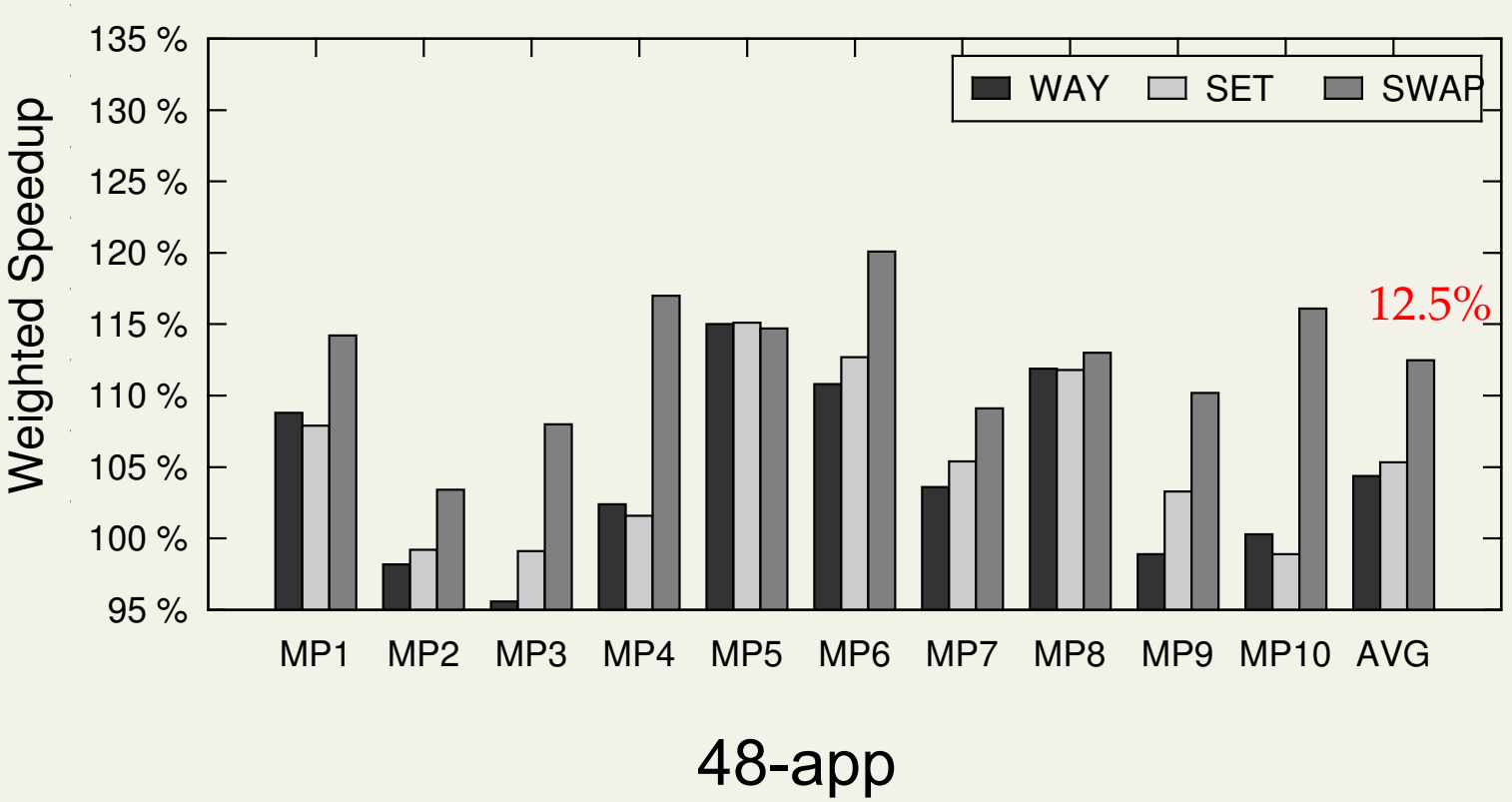
- **Cache miss-ratio curve**
  - Profiling
- **Lookahead algorithm [1] decides partition sizes**
- **Other issues**
  - Hashed indexing
  - Superpage

[1] Qureshi and Patt, MICRO' 06

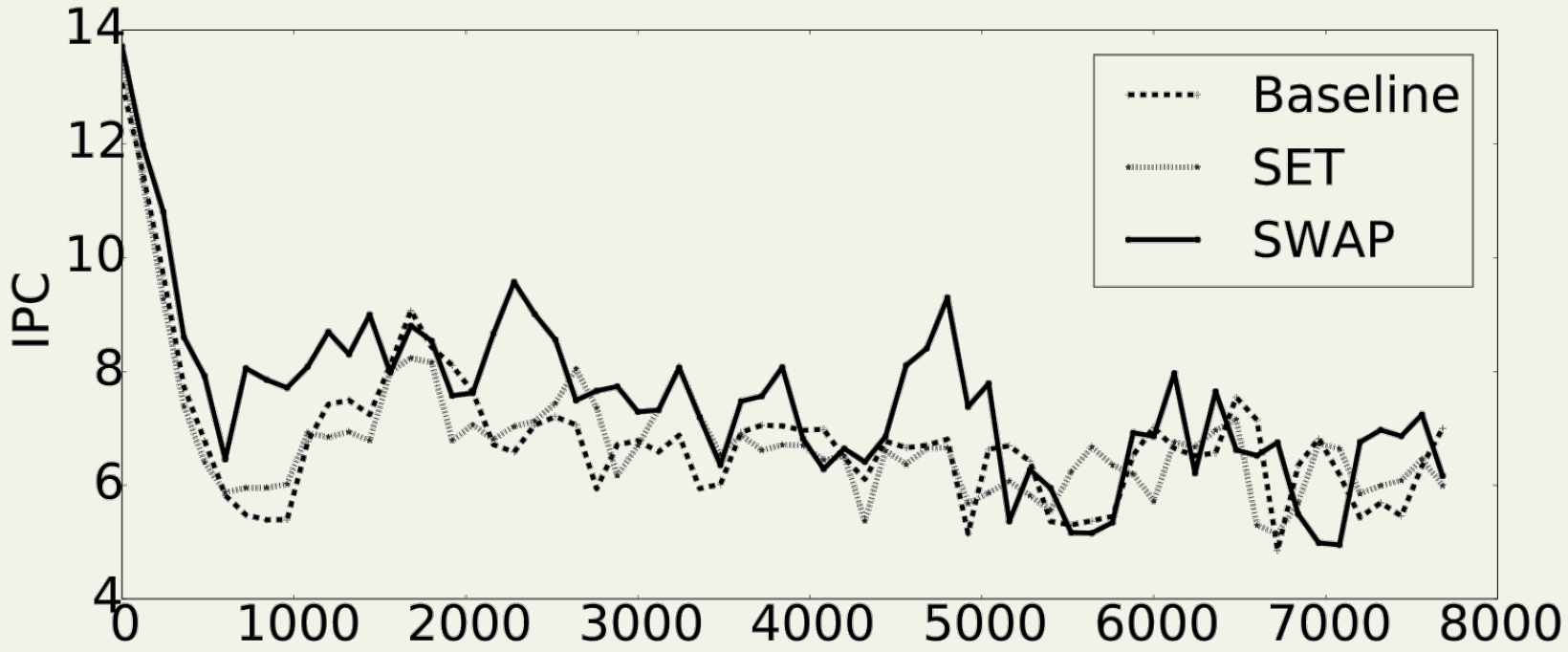
Experimental setup

- **Cavium ThunderX Processor**
  - 48-core CMP, 1.9GHz
  - 16MB shared last-level cache
  - 64GB DDR4-2133, 4 channels
  - Ubuntu Linux 3.18
- **Performance analysis**
  - Mix of SPEC2000 and SPEC2006 multi-programed workloads
  - Latency critical workload memcached

- Running application bundle



- **Running application sequence**
  - The next application in the sequence replaces the finished one; cache partitions change dynamically

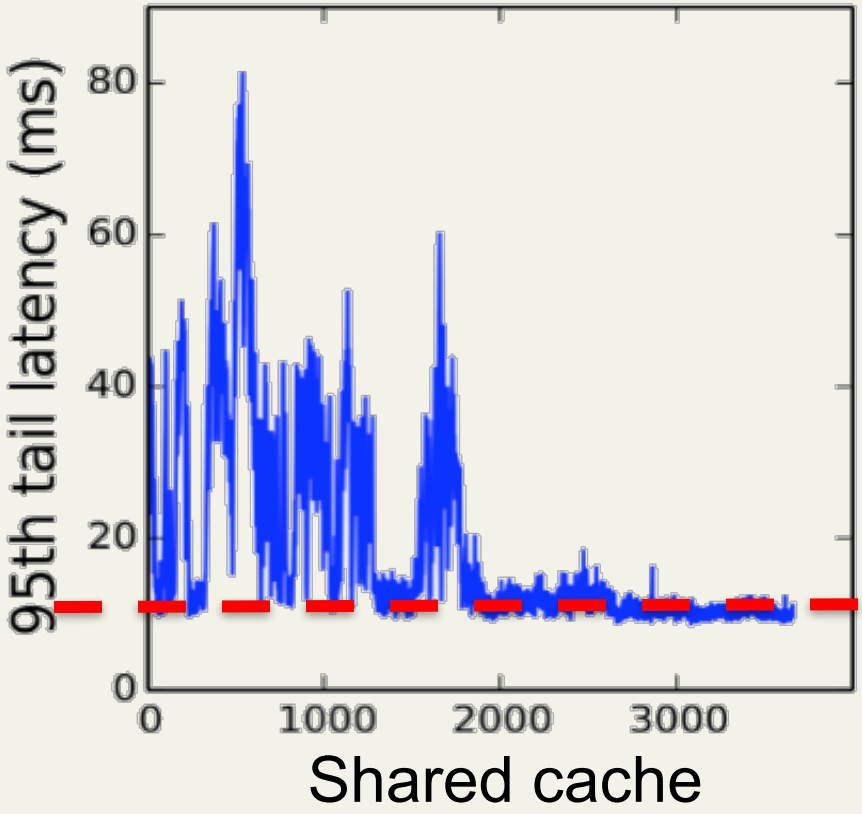


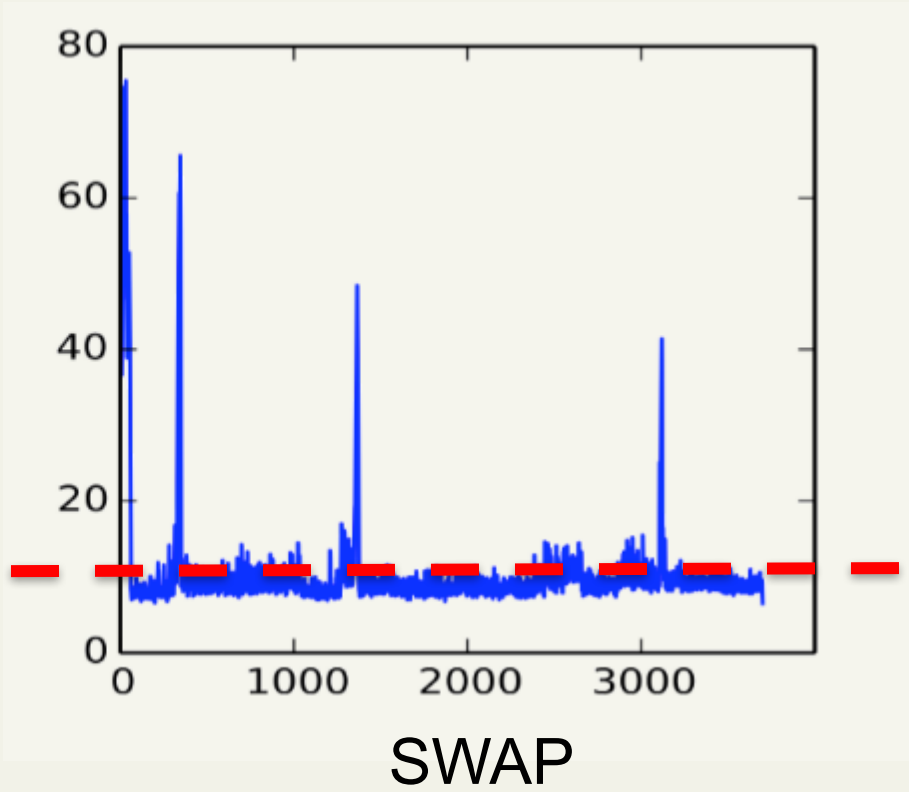
- **Running application sequence**
  - The next application in the sequence replaces the finished one; cache partitions change dynamically

Cores	Seq	WAY	SET	SWAP	Avg. Inj interval
16	1	1.04x	1.02x	1.08x	46s
	2	1.11x	1.04x	1.17x	41s
32	1	0.97x	1.04x	1.11x	31s
	2	1.04x	1.02x	1.20x	25s
48	1	0.92x	0.99x	1.11x	34s
	2	1.00x	1.03x	1.15x	25s

GUARANTEE QOS

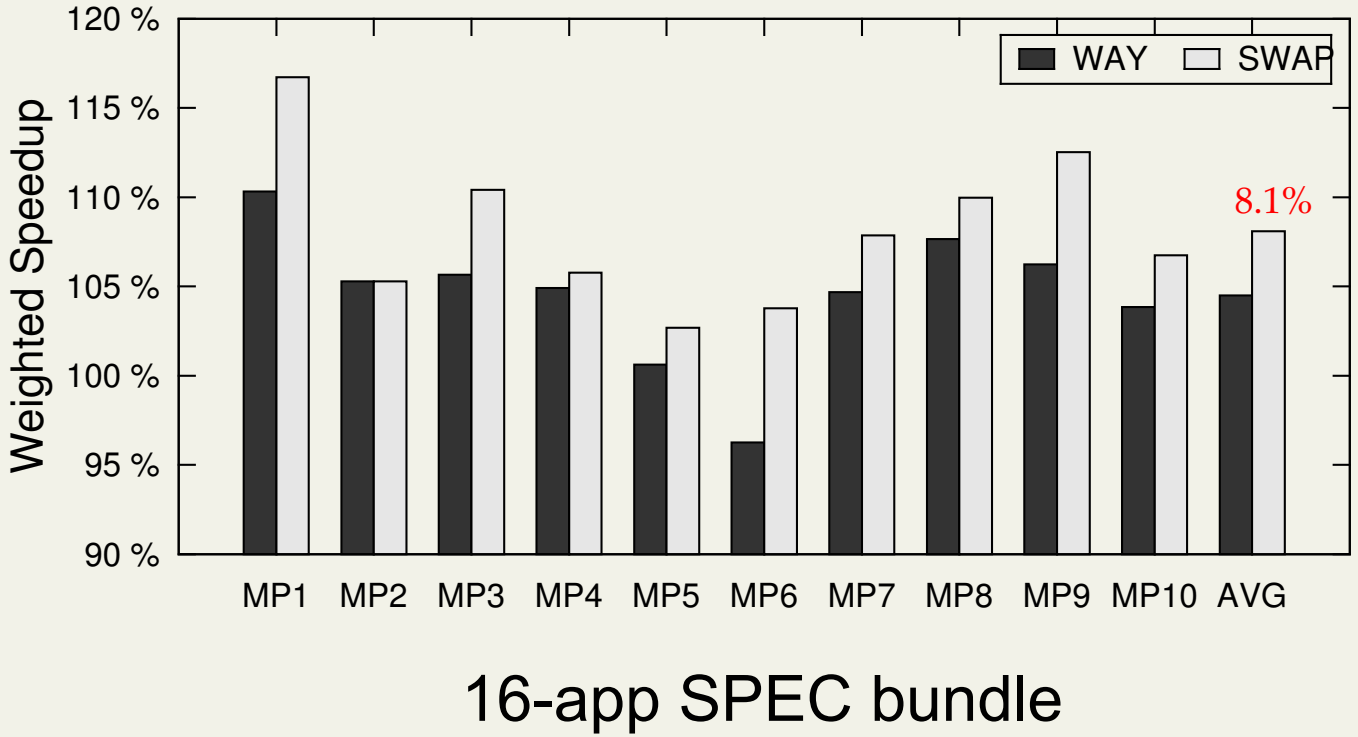
- Latency workload memcached co-located with background multi-programmed workloads





GUARANTEE QOS

- **Latency workload memcached co-located with background multi-programmed workloads**



CONCLUSIONS

- **A real system implementation of fine-grain cache partitioning in large CMP systems**
  - Combine cache way partitioning and page coloring
  - Delivers superior system throughput
  - Guarantee QoS of latency-critical workloads

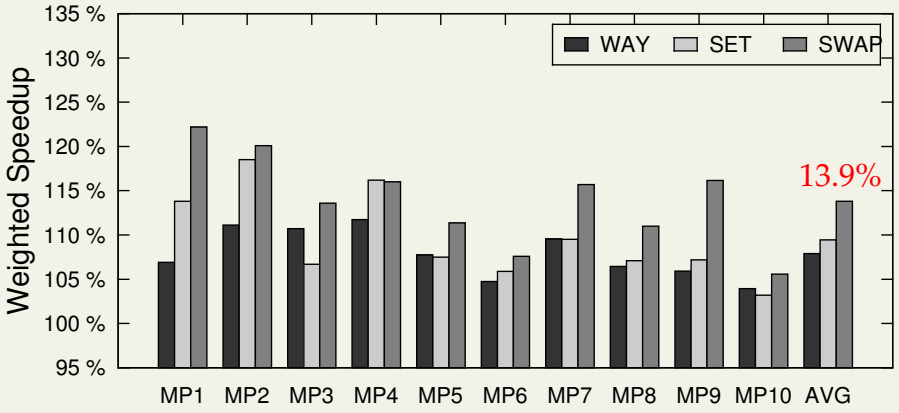
Cornell University
Computer Systems Laboratory

SWAP: Effective Fine-Grain Management of Shared Last-Level Caches with Minimum Hardware Support

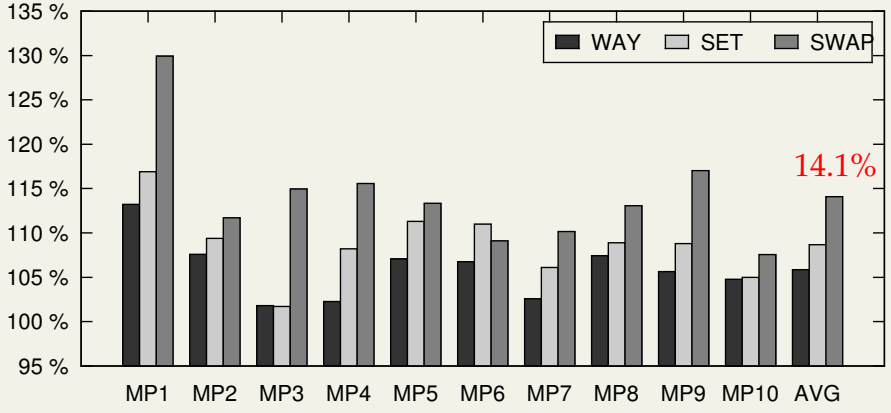
Xiaodong Wang, Shuang Chen, Jeff Setter,
and José F. Martínez

Computer Systems Lab
Cornell University

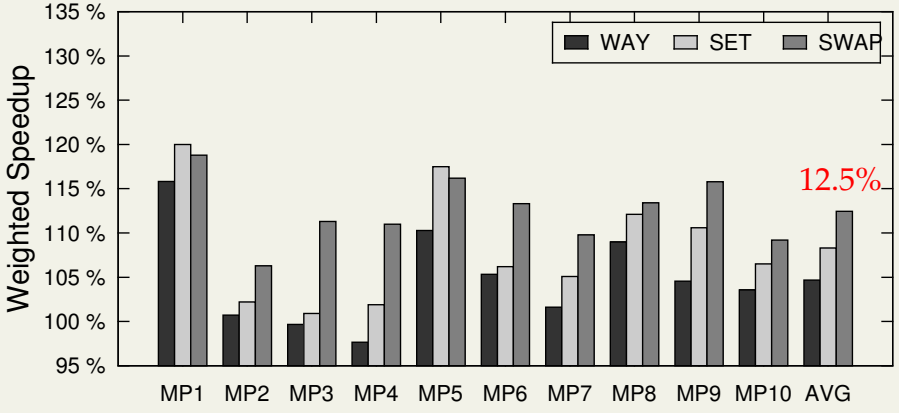
STATIC PARTITIONING



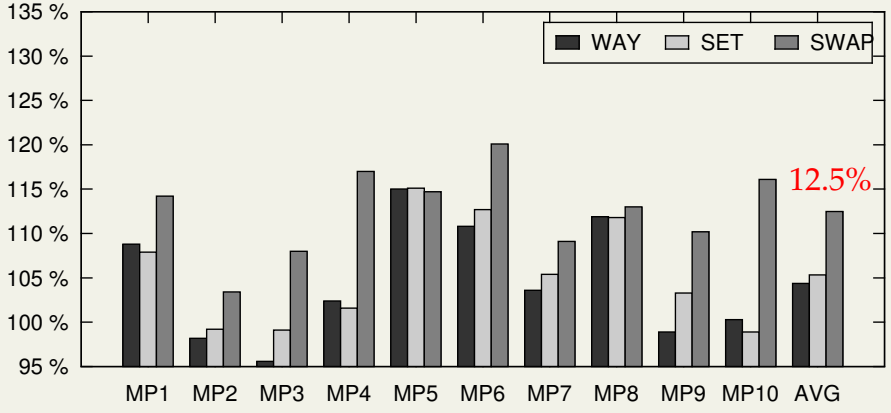
16-core



24-core



32-core



48-core