CMD: Classification-based Memory Deduplication through Page Access Characteristics

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Background

- Limited main memory size is the major bottleneck to consolidate more virtual machines on a hosting server.
  - Increasing number of cores integrated into processor
  - Larger working set of workloads running in VMs.

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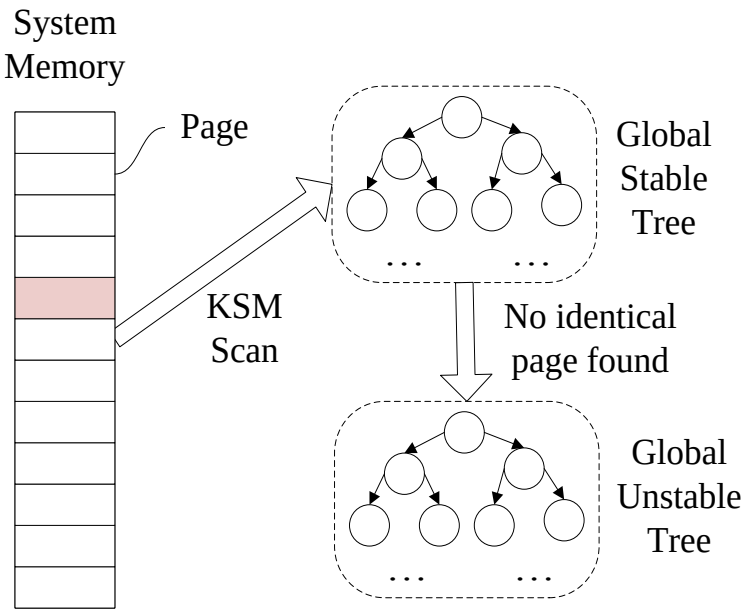
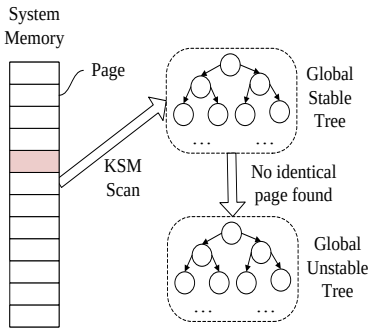
  - Larger working set of workloads running in VMs.
- Content Based Page Sharing (CBPS) is an efficient memory deduplication technique
  - Perform page scan transparently in the hypervisor layer
  - Identical pages (with same content) are detected and shared into a single copy
  - KSM: A widely used implementation of CBPS

KSM

- Kernel Samepage Merging
  - Integrated into Linux kernel archive since 2.6.32
  - The whole memory pages are maintained into two global comparison trees
    - Stable tree: already shared pages with COW protection
    - Unstable tree: pages that are not shared





Problems with KSM

- Pages are directly compared with content (e.g. memcmp in Linux): CPU overhead
- Futile Comparison:
  - Page comparisons that fail to find any page with the same content (including the stable tree and unstable tree)
  - Pages are compared with a large number of uncorrelated pages in the global trees

KSM

- Two parameters to control KSM performance
  - Pages_to_scan: the number of pages to be scanned before sleep, it is 100 by default
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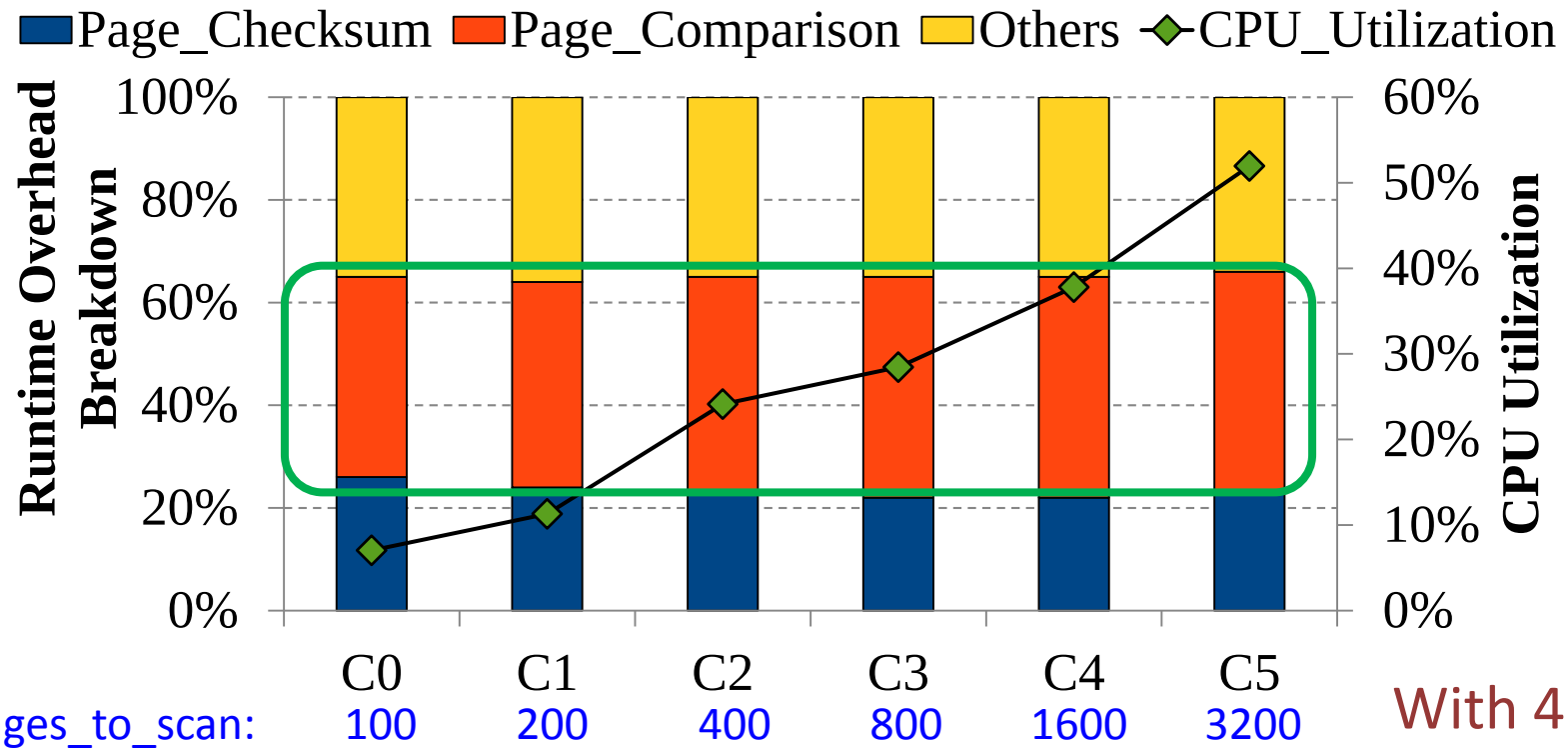
- Two parameters to control KSM performance
  - Pages_to_scan: the number of pages to be scanned before sleep, it is 100 by default
  - Sleep_millisecs: the time to sleep (in milliseconds), it is 20 by default
- KSM run-time overhead breakdown
  - Page Comparison: page content comparison in both global stable tree and unstable tree.
  - Page Checksum: calculating page checksum to determine whether a page is volatile
  - Others: other overhead, such as inserting pages in the tree, break COW when a shared page is written

Outline

- Background & Motivation
  - The profiling of KSM
- CMD: **C**lassification based **M**emory **D**eduplication
- Experimental Results
- Conclusion

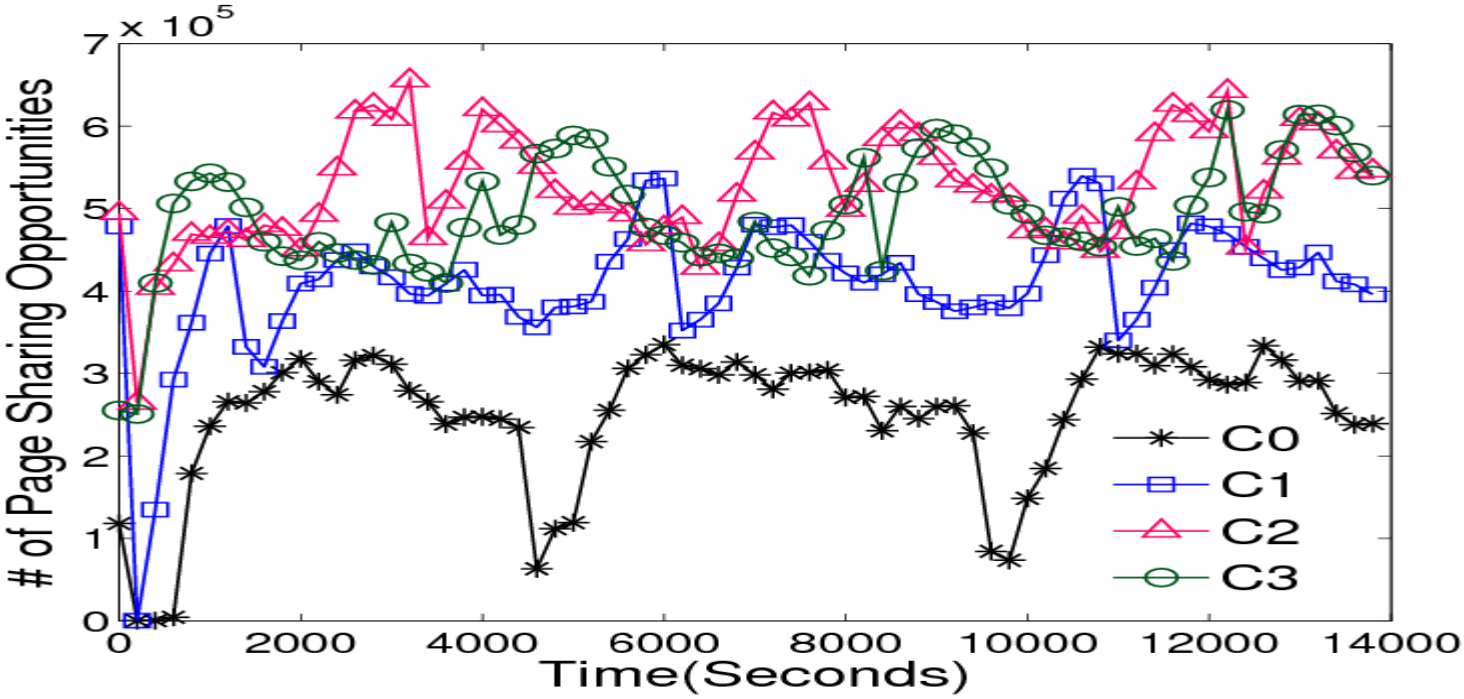
Motivation: Profiling of KSM

- The page_comparison contributes about 44% of the overall run-time overhead
- The CPU Utilization increases as more frequent page comparisons:
  - It is about 7% for C0, 24% for C2 and up to 52% for C5



Motivation

- With more frequent page comparisons, the KSM can detect more page sharing opportunities
  - Detect more short-lived page sharing quickly



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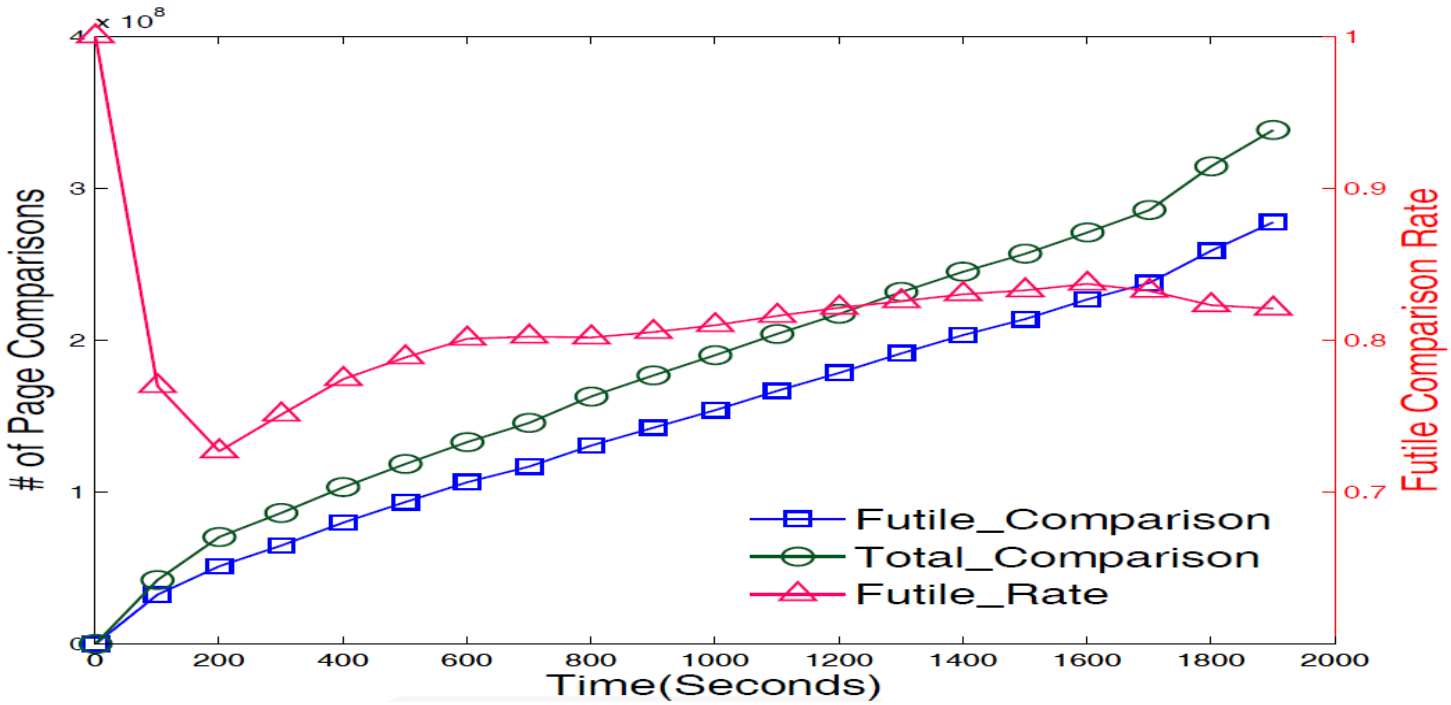
- The total page comparison and futile comparison increase proportionally as the KSM scans periodically



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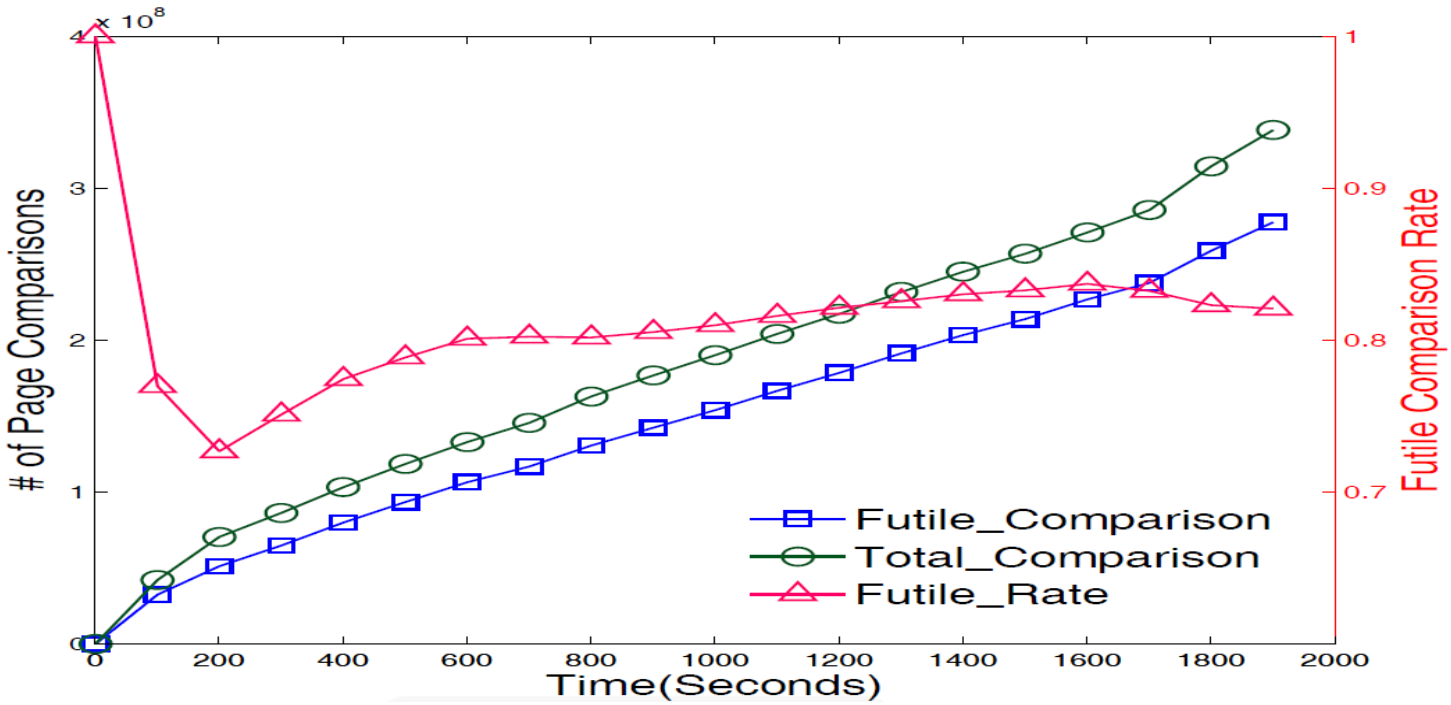
- Futile_Rate: the ratio between Futile_Comparison and Total_Comparison
  - It becomes steady at about 83%



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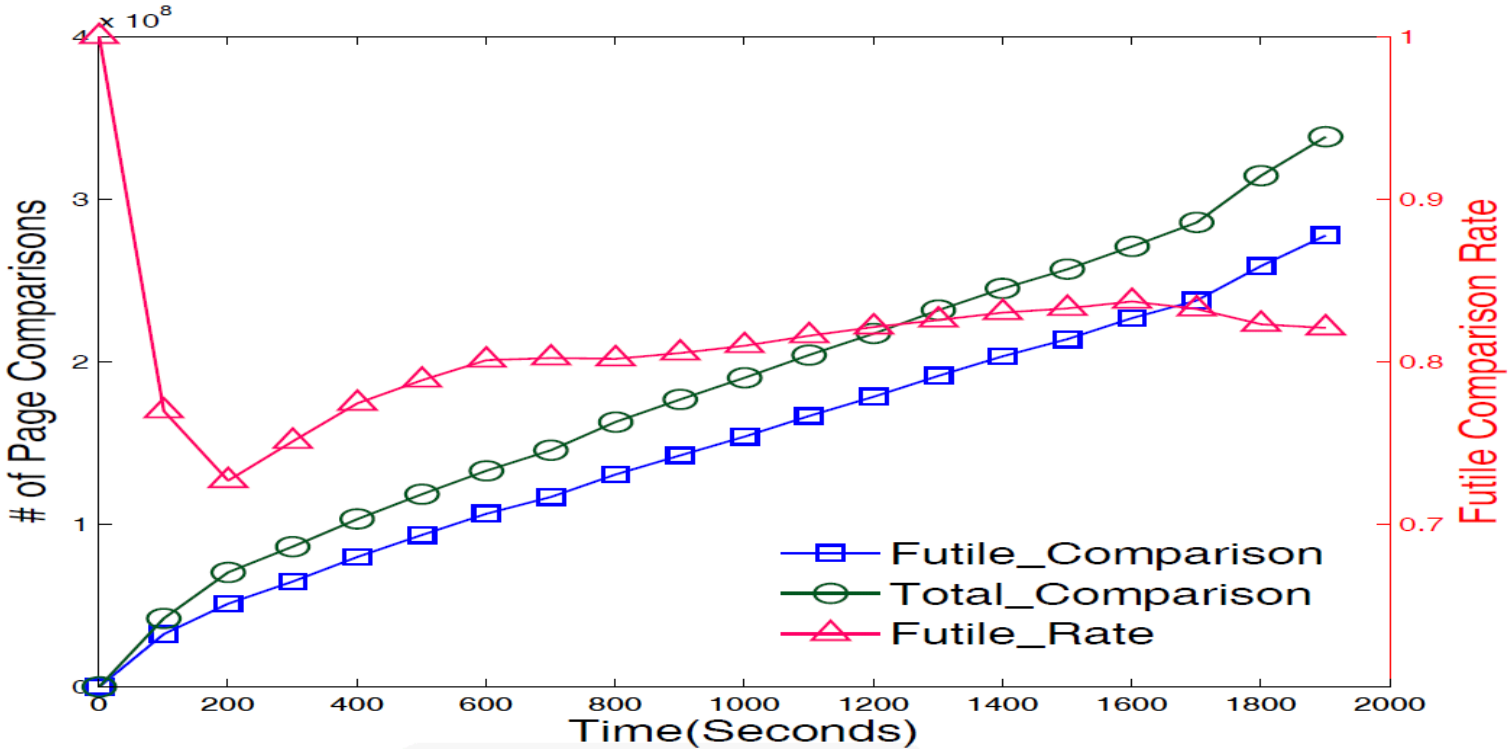
More frequent scan can detect more page sharing opportunities, but it also results in a large number of futile page comparisons and thus heavy CPU overhead



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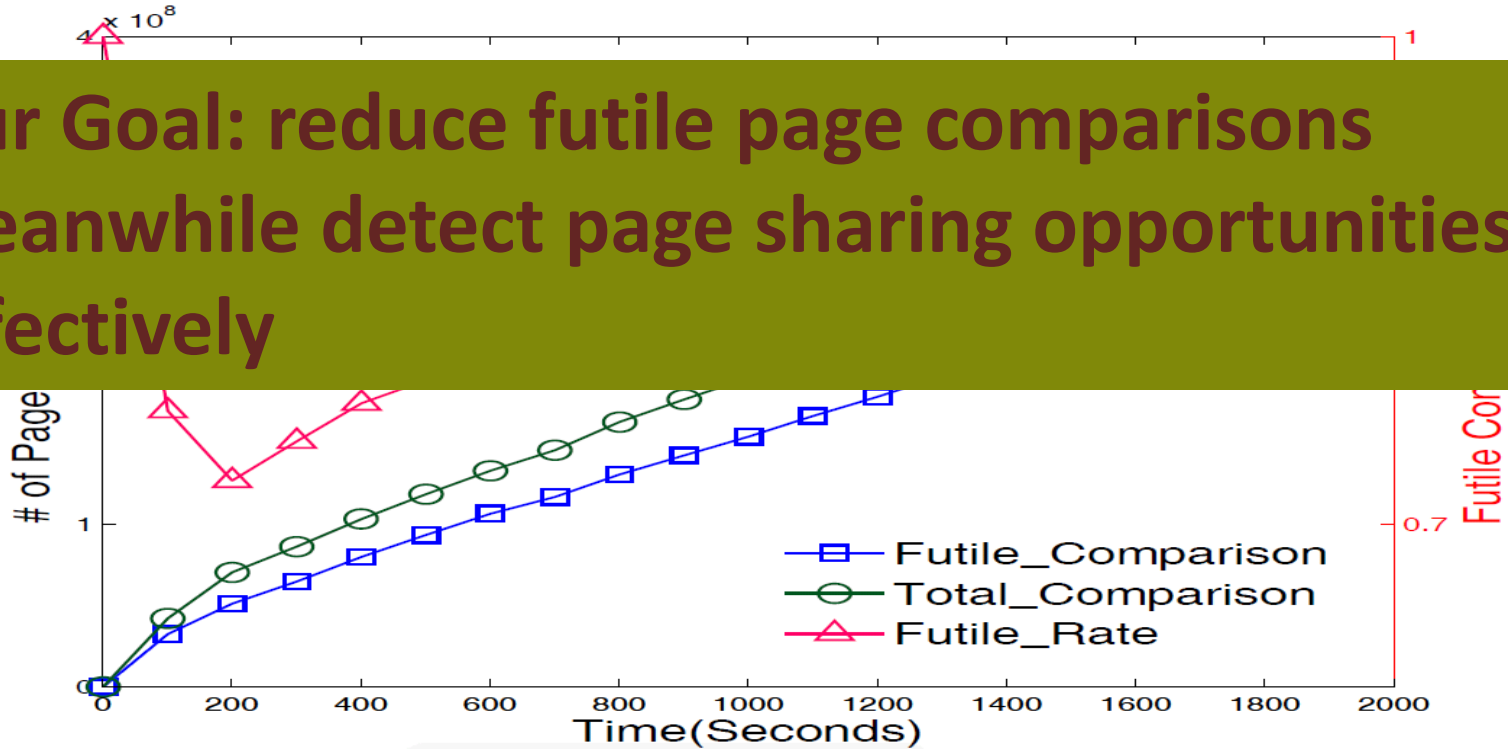
Our Goal: reduce futile page comparisons meanwhile detect page sharing opportunities effectively



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The Overview of CMD

Physical Address Trace

0x398f24a, r
0x398f24b, r
0x398f24c, w
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0x1af4aa, w
0x1af4a6, r
0x1af4a8, w
……
0x38d2cfc, r
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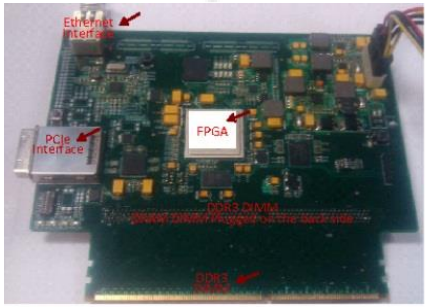
……



Page Access Monitor

The Overview of CMD

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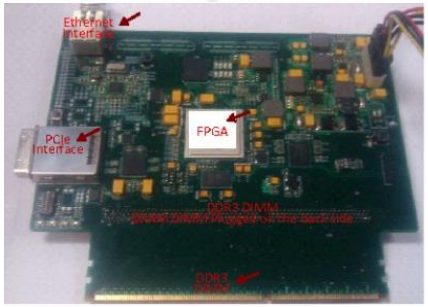
pfn

Page Access Characteristics

0	12	17	25	8
1	31	28	2	11
2	3	0	53	1
	……			
N-2	0	0	0	0
N-1	36	0	0	1



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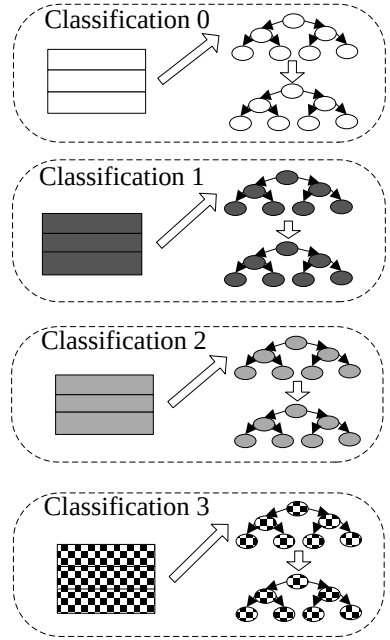
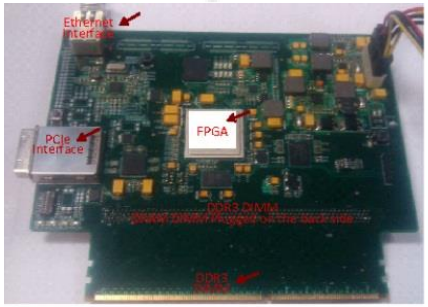
Page Classification

Classification based KSM





Page Access Monitor

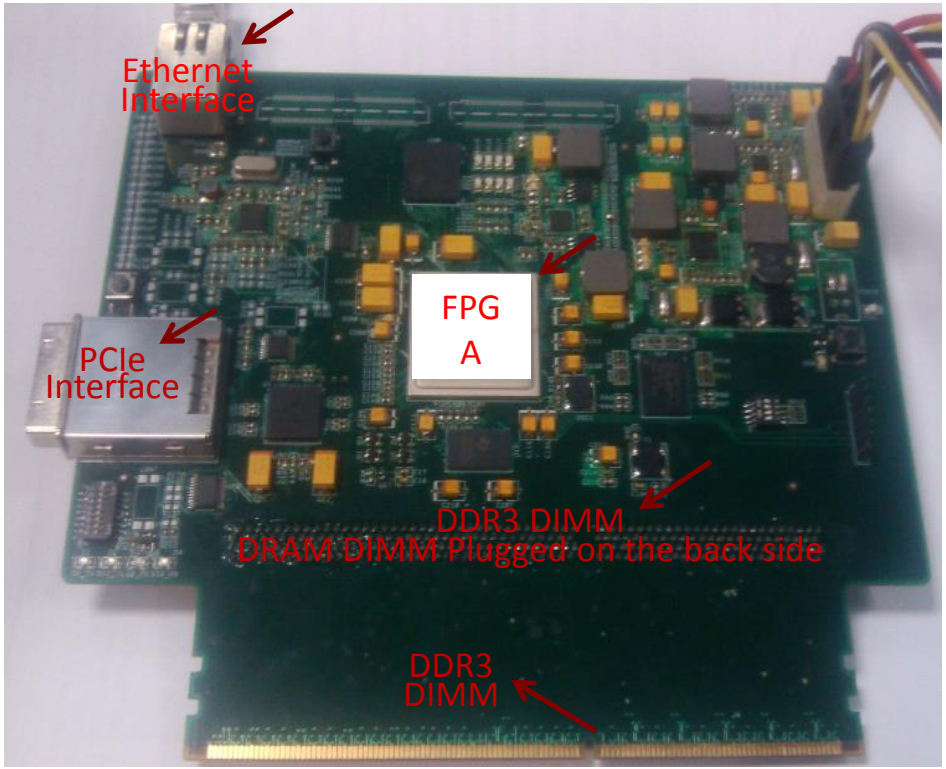
Linux

Page Access Monitor

- HMTT: Hybrid Memory Trace Toolkit
  - A DDR3 SDRAM compatible memory monitoring system
  - Adopts hardware snooping technology

Memory Trace:

- Fine granularity: cache block
- <time_stamp, r/w, phy_addr>



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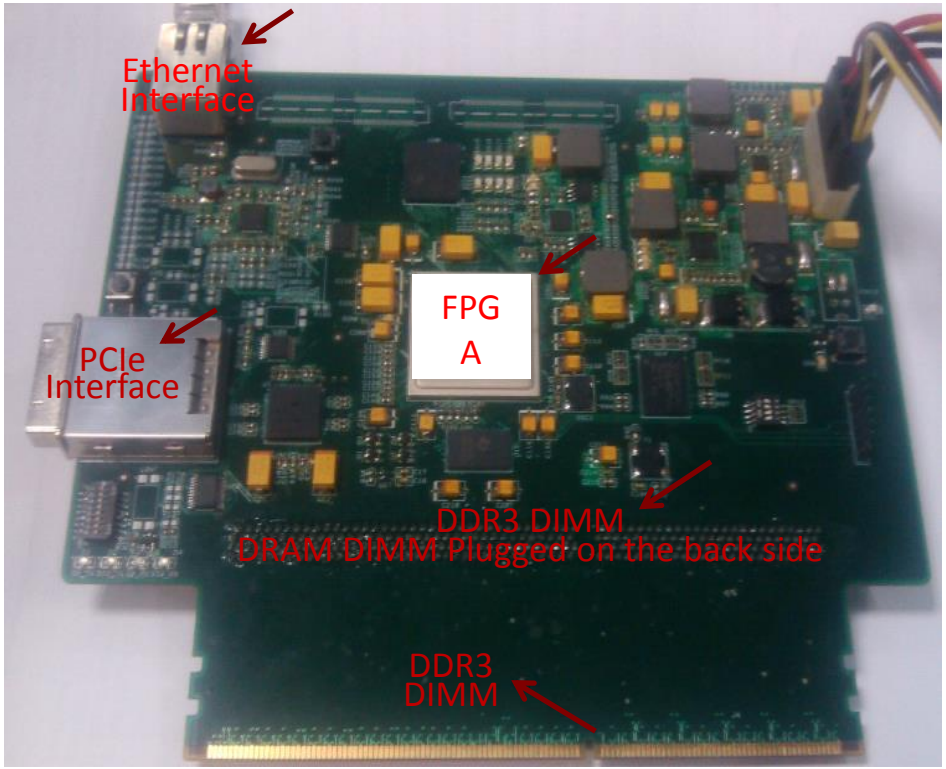
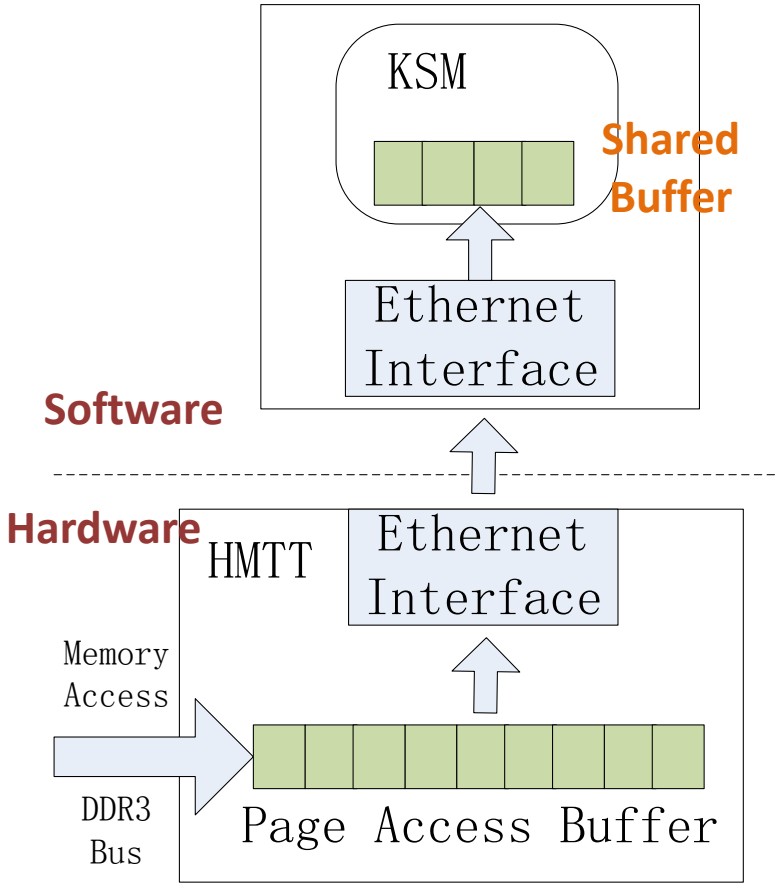
Advantages:

- Platform independent
- Negligible overhead
- Full-system real memory traces



Pace Access Characteristics

- Page Access Characteristics are maintained by the HMTT
  - E.g. write access count of a page, write distribution of sub-pages
  - Implement a Page Access Buffer on the HMTT
  - Updated in the buffer when a memory access is monitored



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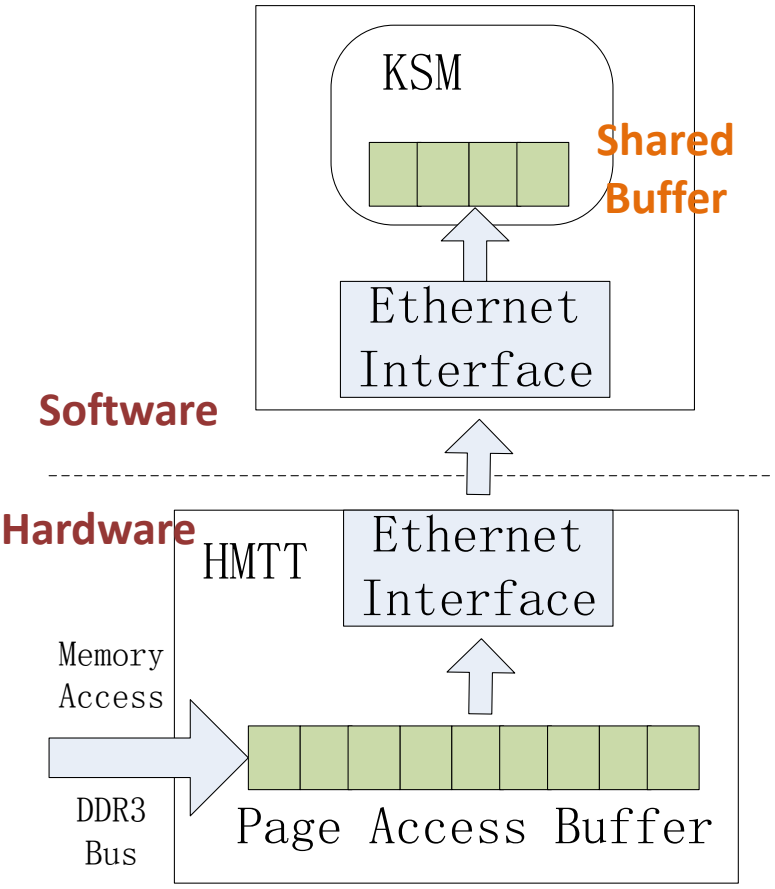
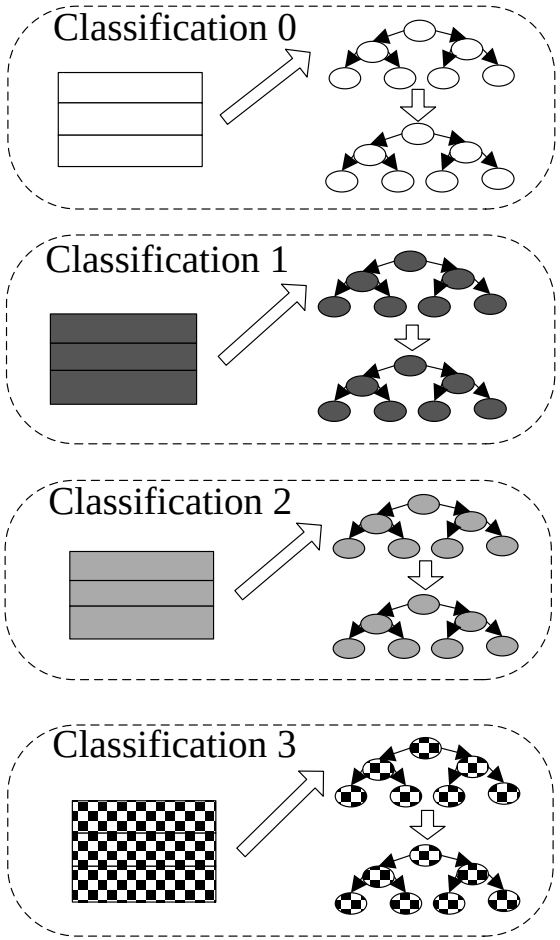
  - Implement a Page Access Buffer on the HMTT
  - Updated in the buffer when a memory access is monitored
- Fed back to the software (KSM) periodically through Ethernet Interface
  - We have implemented a shared (software) buffer as a kernel module
  - The KSM thread can utilize it to perform page classification and CMD



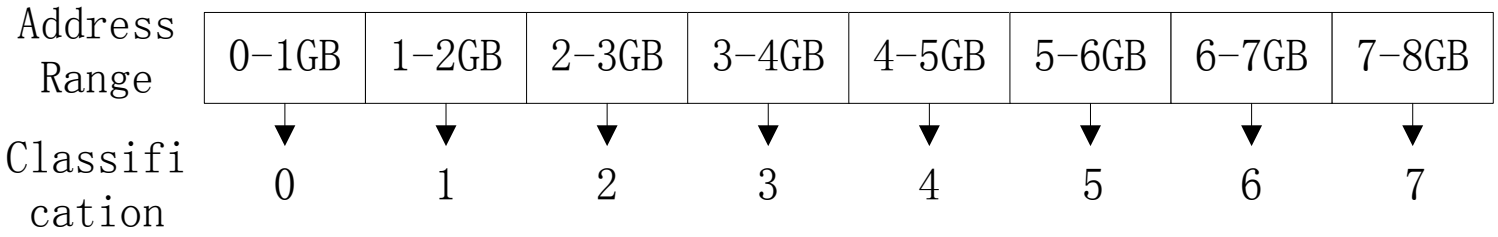
Classification on KSM

- The large global comparison trees are divided into multiple small trees
  - Pages are grouped into classifications based on page access characteristics
  - Local comparison trees dedicated to each page classification
  - Pages are just compared with nodes in the local trees
  - Pages from different classifications are never compared, probably result in futile comparisons



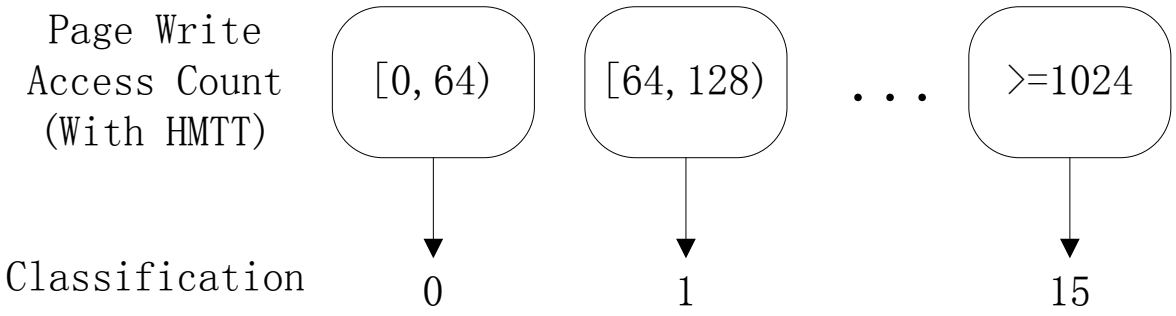
Page Classification Approaches

- We have implemented 3 different page classification approaches
- 1. CMD_Address (CMD_Addr):
  - Pages are classified based on physical address (pfn)
  - Static and simple, but page-access unaware
  - E.g. 8GB memory is evenly divided into 8 classifications



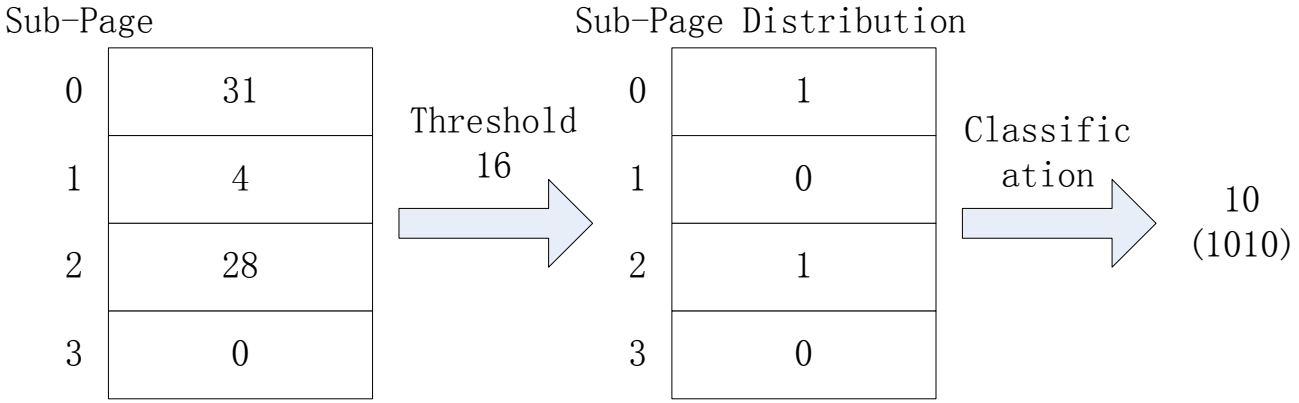
Page Classification Approaches

- 2. CMD_PageCount:
  - Pages are classified based on write access count.
  - Write access modifies page content and thus affects page sharing opportunities.
  - Page-access aware, slightly improve page classification accuracy, but still coarse granularity
  - E.g. page count threshold is set to 64

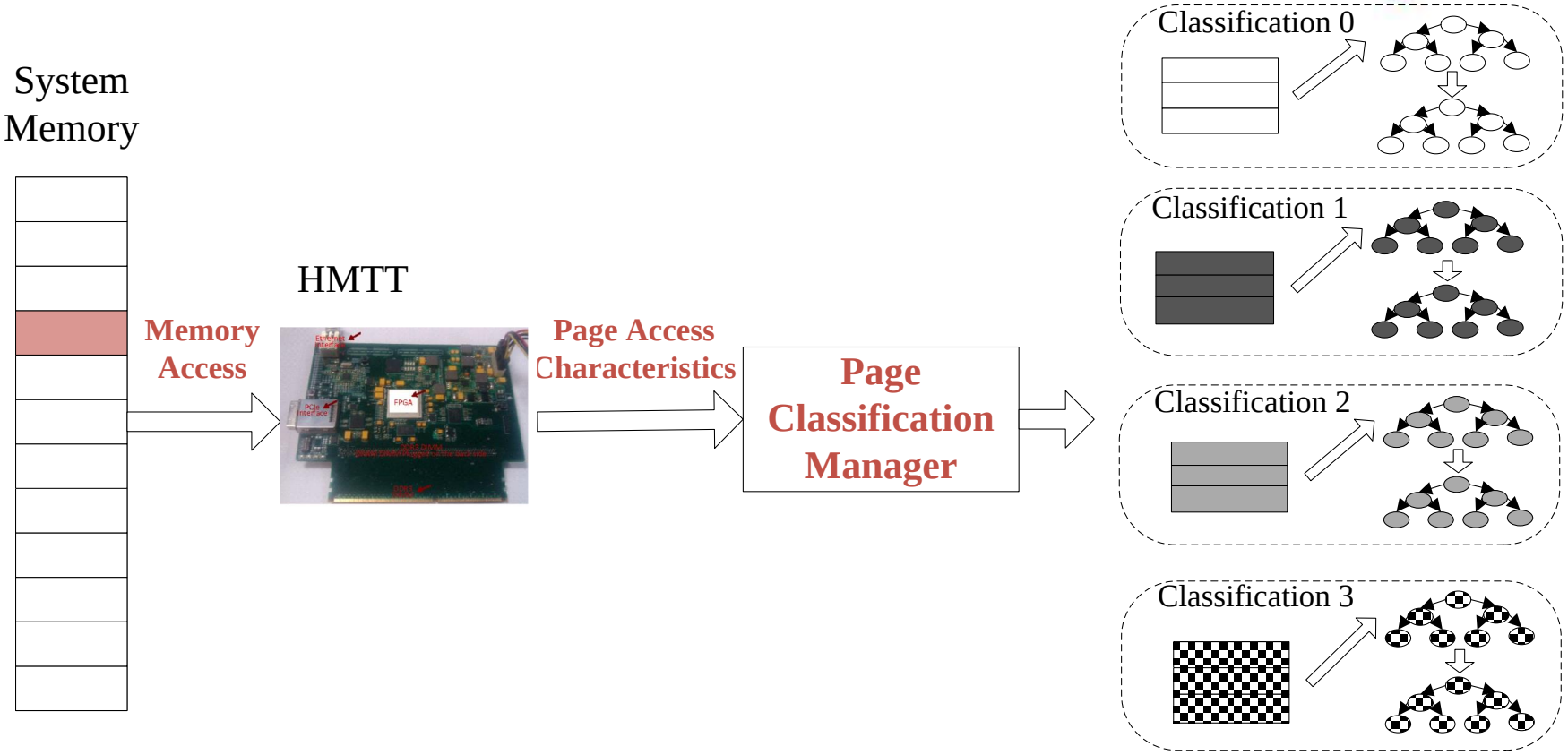


Page Classification Approaches

- 3. CMD_Subpage_Distribution:
  - Pages are divided into multiple sub-pages, and we monitor write access count on sub-page granularity
  - Pages are classified based on the write distribution of sub-pages
  - Fine granularity, improve classification accuracy
  - E.g. 4 sub-pages with write threshold of 16



Put them all together



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Experimental Methodology

- Intel Xeon E5504 processor (2GHz)
  - 4 physical cores with Hyper-Thread disabled
  - 3-level cache, 16-way 4MB shared L3 cache
- Dual-ranked DDR3-800MHz physical memory, 8GB capacity in total

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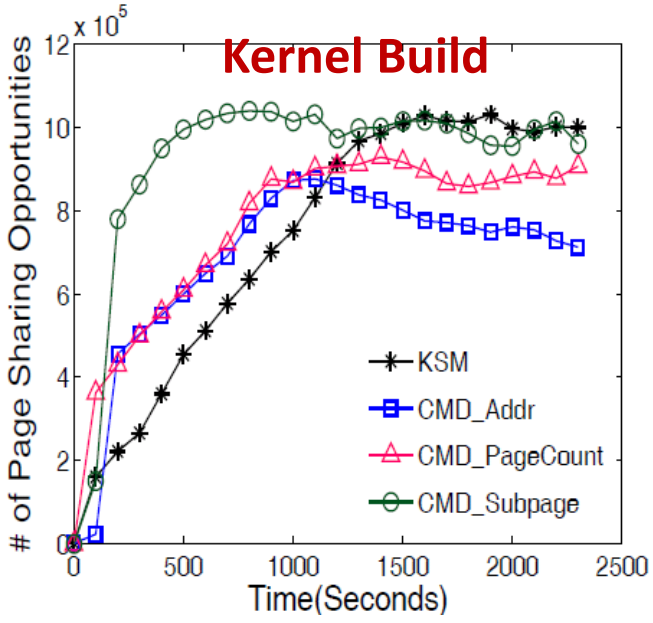
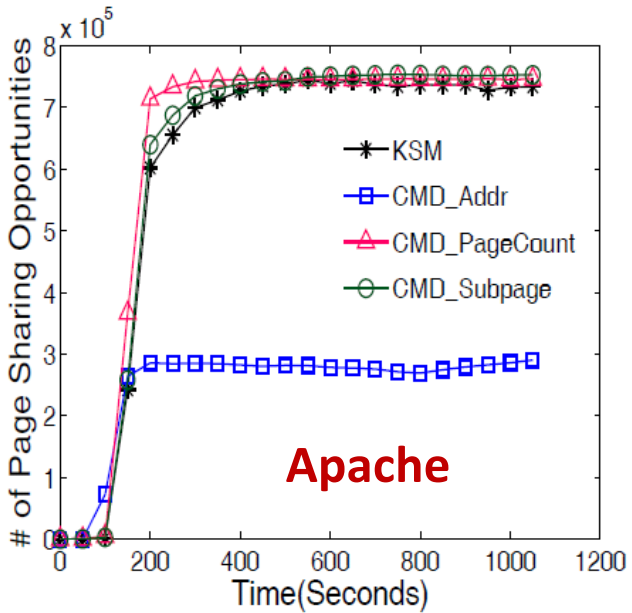
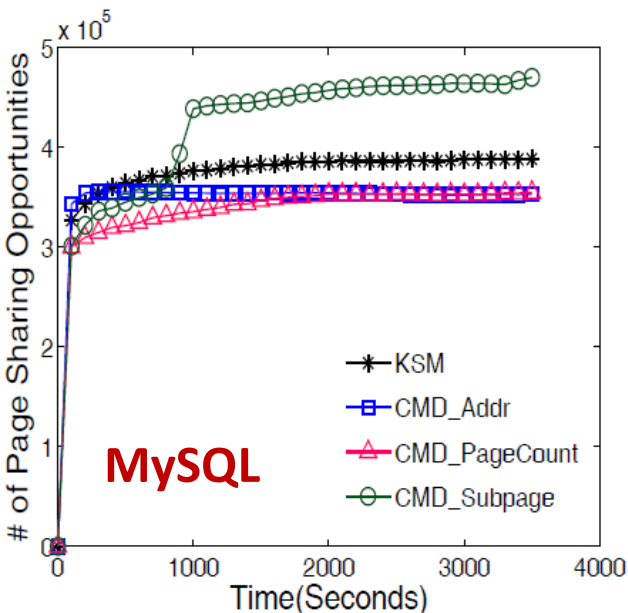
- Dual-ranked DDR3-800MHz physical memory, 8GB capacity in total
- Host server: CentOS 6.2 with Linux kernel 3.6.10 (implement CMD)
- We adopt libpcap to capture fed-back Ethernet packets from HMTT
- QEMU with KVM (qemu-kvm-1.2.0) to support guest VMs:
  - 4 VMs as default, each with 1 virtual CPU and 2GB memory
- Guest VMs: CentOS 6.3 with Linux kernel 2.6.32-279
- Workloads: Kernel Build, Apache (ab), MySQL (SysBench)

Page Sharing Opportunities

- CMD_Addr fails to detect page sharing opportunities, it is worst for Apache with ~39% compared with KSM
- CMD_PageCount is medium, it is about 87% of KSM for Kernel Build workload
- CMD_Subpage has the best ability to detect page sharing opportunities, it can even detect more page sharing for the MySQL workload
  - Because it can detect more short-lived page sharing

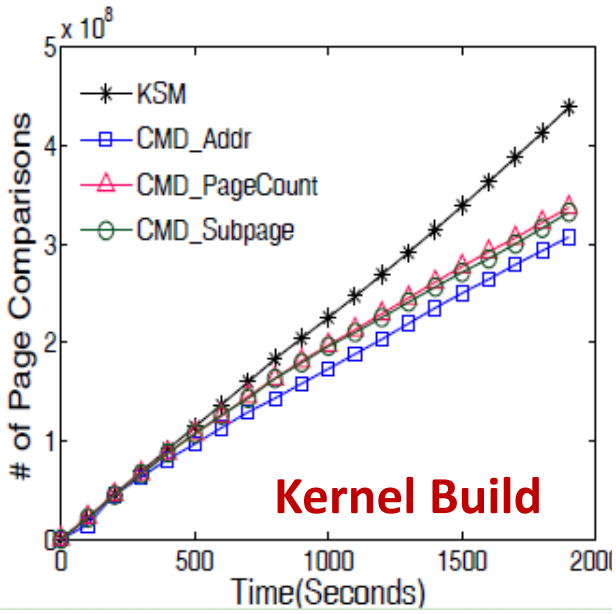


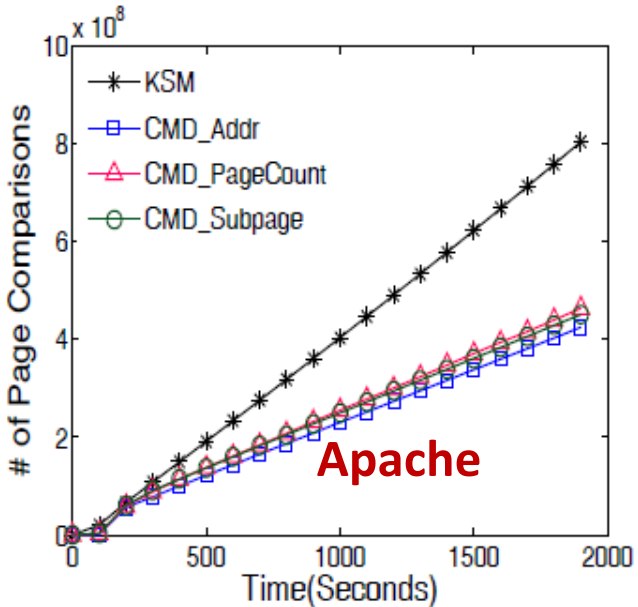


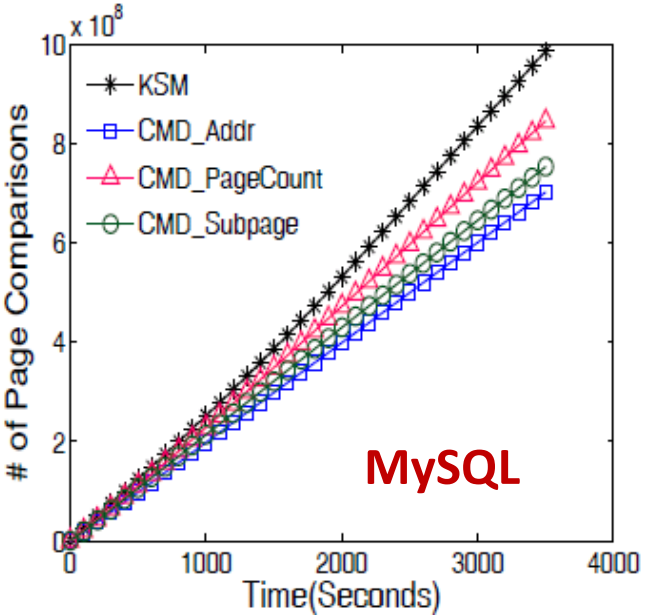


Page Comparisons

- CMD_Addr can reduce the most page comparisons, because it divides the global trees in most balance
- CMD_Subpage can also effectively reduce page comparisons

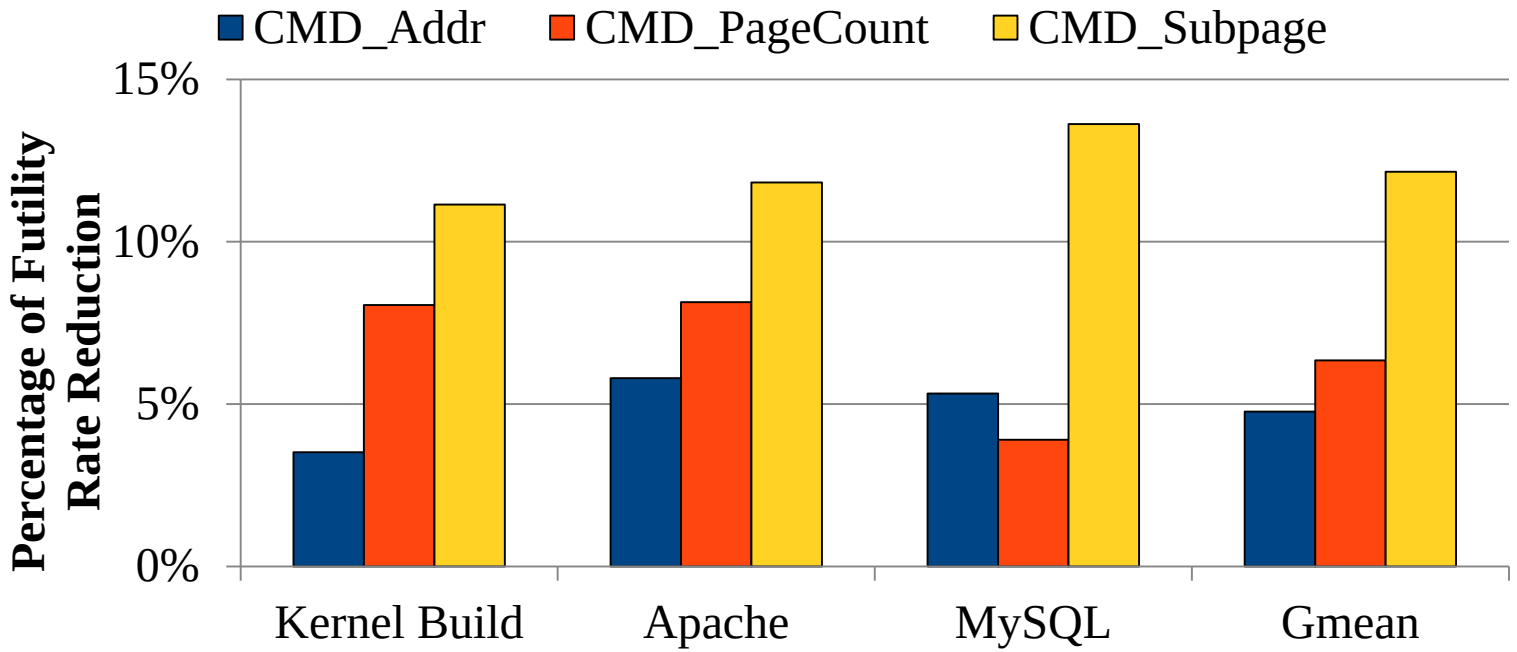






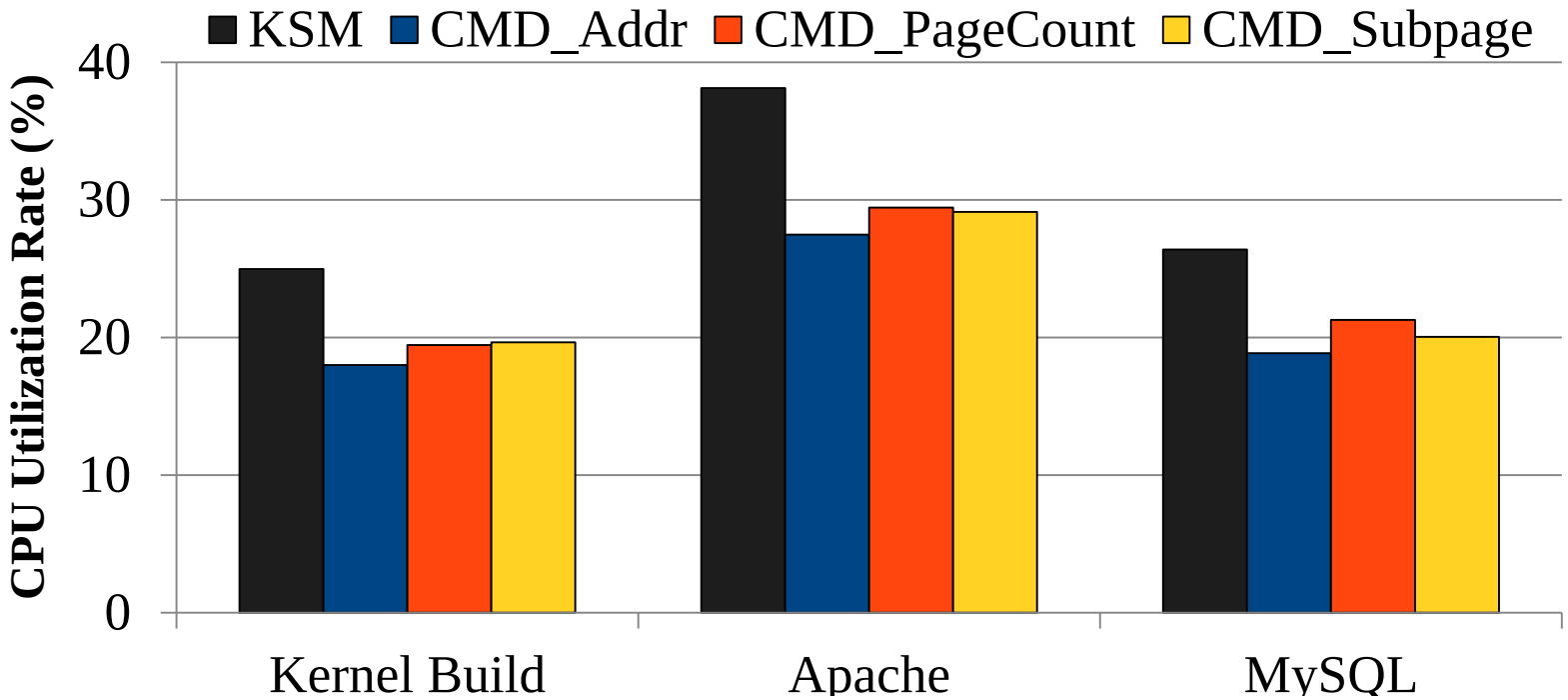
Futile Rate Reduction

- CMD_Addr can reduce the least futile rate by about 4.8%
- CMD_PageCount can reduce by about 6.4%
- CMD_Subpage can reduce the most by about 12%
  - But it still has space to find the best page classification approach



CPU Utilization Reduction

- The CPU Utilization of the KSM thread (ksmd) is got from top measurements taken every second
- All of the three approaches can reduce CPU Utilization because of the reduction of page comparisons



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- We perform a detailed profiling of KSM
  - Page comparison contributes a certain portion of the overall KSM run-time overhead
  - There exists massive futile comparisons because of adopting two large global comparison trees
- We propose a lightweight approach called CMD
  - Pages are divided into different classifications based on page access characteristics with the help of HMTT
  - It maintains local comparison trees dedicated to each page classification, and pages comparisons are just performed in local.
  - CMD can reduce futile comparisons, meanwhile detect page sharing opportunities effectively

HMTT Homepage: http://asg.ict.ac.cn/hmtt/

Thanks !

&*Questions?*