CMD: Classification-based Memory Deduplication through Page Access Characteristics

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• **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.
Background

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  – Increasing number of cores integrated into processor
  – 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
  - `Sleep_millisecs`: the time to sleep (in milliseconds), it is 20 by default
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  – Pages_to_scan: the number of pages to be scanned before sleep, it is 100 by default
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• 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: Classification based Memory Deduplication

• 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
Motivation

• 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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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.

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

......

0x1af4aa, w
0x1af4a6, r
0x1af4a8, w

......

0x38d2cfc, r
0x38d2cfd, w

......
## The Overview of CMD

### Physical Address Trace

- 0x398f24a, r
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- 0x38d2cfc, r
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### Page Access Characteristics

<table>
<thead>
<tr>
<th>pfn</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12 17 25 8</td>
</tr>
<tr>
<td>1</td>
<td>31 28 2 11</td>
</tr>
<tr>
<td>2</td>
<td>3 0 53 1</td>
</tr>
<tr>
<td>N-2</td>
<td>0 0 0 0</td>
</tr>
<tr>
<td>N-1</td>
<td>36 0 0 1</td>
</tr>
</tbody>
</table>

Page Access Monitor
The Overview of CMD

Physical Address Trace

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Page Access Monitor

Classification based KSM

- Classification 0
- Classification 1
- Classification 2
- Classification 3
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>
Page Access Monitor

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Memory Trace:
  • Fine granularity: cache block
  • <time_stamp, r/w, phy_addr>

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

<table>
<thead>
<tr>
<th>Address Range</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1GB</td>
<td>0</td>
</tr>
<tr>
<td>1–2GB</td>
<td>1</td>
</tr>
<tr>
<td>2–3GB</td>
<td>2</td>
</tr>
<tr>
<td>3–4GB</td>
<td>3</td>
</tr>
<tr>
<td>4–5GB</td>
<td>4</td>
</tr>
<tr>
<td>5–6GB</td>
<td>5</td>
</tr>
<tr>
<td>6–7GB</td>
<td>6</td>
</tr>
<tr>
<td>7–8GB</td>
<td>7</td>
</tr>
</tbody>
</table>
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 Write Access Count Diagram](image)
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:

<table>
<thead>
<tr>
<th>Sub-Page</th>
<th>Write Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>31</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-Page Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold 0101</td>
</tr>
<tr>
<td>01</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

Classification: 10 (1010)
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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  – 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
• 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

[Graphs showing page sharing opportunities for Kernel Build, Apache, and MySQL]
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.

![Graphs comparing page comparisons over time for Kernel Build, Apache, and MySQL](image-url)
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

![Chart showing percentage of futility rate reduction for Kernel Build, Apache, MySQL, and Gmean with different page classification methods.](chart.png)
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.

![CPU Utilization Rate Graph](image)
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  – 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
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  – 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?