Difference Engine: Harnessing Memory Redundancy in Virtual Machines
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Why Share Memory?

- Server consolidation saves money and energy.
- Memory is a key bottleneck for VM consolidation.
- Sharing enables memory over-commitment.
Memory Over-Commit Mechanisms for Virtualization

- **Ballooning** - well established, drivers widely available

- **Page Sharing**
  - **Collaborative** (e.g. Satori: Enlightened Page Sharing, by Milos et al.) - requires guest modification (paravirtualization) or **by hypervisor only** (unmodified guest OS - full virtualization)?
  - **Content based** or **by tracking changes** (faster, requires guest changes, e.g., Satori)
  - **Whole pages** (Waldspurger of VMware, OSDI’02) or **sub-pages**?

- **Paging** - orthodox but slow
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Outline

1. Design
   - Sharing
   - Patching
   - Compression
   - Paging

2. Implementation

3. Evaluation
   - Times of Individual Operations
   - Clock
   - Isolated Mechanisms
   - Real World Workloads
   - Aggregate System Performance

4. Conclusions

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Cascade of Mechanisms

Initial $\Rightarrow$ Share, Patch, Compress, Page
Sharing

- Identify: Hash collision + verification
- Share: directing guest pages to the same physical page, read only
- Break: Copy On Write (COW)
- Clean: when 0 references
Mixed Real-World Workloads

Each VM with 512 MB. Stressing memory. Following VMmark (VMware), VMbench (Moeller, PhD thesis)

1. Mixed-1
   1. Windows, running RUBiS (e-commerce: Apache+MySQL)
   2. Debian, compiling Linux kernel
   3. Slackware, compiling Vim, then running lmbench (memory, network, filesystem, signals....)

2. Mixed-2
   1. Windows, Apache with 32K static pages requested by external httperf
   2. Debian, Sysbench (db) with 10 threads creating 100K requests
   3. Slackware, dbench (filesystem) with 10 clients for 6 minutes, then IOZone (filesystem)
Potential Estimate for Patching and Sharing

- Ran Mixed-1
- Suspended the VM after completing the benchmark
- Took memory snapshot
- Computed patches with XDelta (FOSS binary diff)
- Patch limit: 2K (half a page), average patch: 1K
- Zero pages appear less when VMs get less memory, when scrubbing is used less, when Linux caches more files

<table>
<thead>
<tr>
<th>Pages</th>
<th>Initial</th>
<th>After Sharing</th>
<th>After Patching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unique</td>
<td>191,646</td>
<td>191,646</td>
<td></td>
</tr>
<tr>
<td>Sharable (non-zero)</td>
<td>52,436</td>
<td>3,577</td>
<td></td>
</tr>
<tr>
<td>Zero</td>
<td>149,038</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>393,120</td>
<td>195,224</td>
<td>88,422</td>
</tr>
<tr>
<td>Reference</td>
<td></td>
<td>50,727</td>
<td>50,727</td>
</tr>
<tr>
<td>Patchable</td>
<td></td>
<td>144,497</td>
<td>37,695</td>
</tr>
</tbody>
</table>

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HashSimilarityDetector(k,s),c

- Hash $k \cdot s$ randomly chosen 64-byte block locations on the page
- Group to $k$ groups, each group is an index in the hash table
- HashSimilarityDetector(2,1): two keys for each page, two indexations (a candidate needs to match only one)
- $c$: number of different pages stored for each key (choose the best patch among the stored pages)
- Smaller $k,s,c \Rightarrow$ less resources used
Savings from Patching Only as Function of $k, s, c$

\[
\text{mem savings} = 100\% \cdot \left(1 - \frac{\text{used}}{\text{allocated to VMs}}\right)
\]

Chosen: 2 hash keys of single locations. 1 stored page. 18-bit hashes (32 bit hashes yields: 25\% instead of 20\% for mixed-1).
Compression

- When:
  - Compression ratio is high enough.
  - Page is infrequently accessed - “Not Recently Used” (NRU).
  - Page is unique.
- Compressed page is invalidated, so the hypervisor knows when to decompress it.
- Pluggable: currently supports
  - LZO (Lempel-Ziv, very fast decompression, trade-off between compression speed and quality)
  - WKdm (fast encoding)
- Decompressed page remains open in memory until considered for compression again.
Paging

- Involves disk I/O - slow
- Extends beyond physical memory
- Candidates — NRU
- Swapped out pages cannot be shared or referenced for patching
- Safety net
Changes to Xen

- 14.5K lines added + 19K lines for existing libraries
- Changes mainly in guest physical to machine table, and in the shadow page tables
- Difference Engine (DE) not in effect during boot, only when shadow page tables are used
- Not touching Dom0 to avoid circularity
- ioemu (IO emulator, in Dom0) changed to map only several guest pages to Dom0.
- Block allocator - to efficiently manage storage of compressed and shared pages (consume less than one page).
Clock used to find NRU pages.

- Each invocation
  - Resets Read, Modified bits
  - Scans a part of memory
  - Returns limited-size list of NRU pages

- Invocations at least 4 seconds apart

- Xen’s shadow page tables code modified: setting those R/M bits in the guest physical to host physical map, based on the shadow page tables.
Clock Conditions: Policy/Mechanism Separation

recently = since last scan

1. C1 — Recently modified
2. C2 — Recently read only
3. C3 — Recently nothing
4. C4 — Nothing for several scans (needs 2 additional bits)
Clock Conditions: Policy/Mechanism Separation

Default Policy:

1. C1 — Recently modified
2. C2 — Recently read only
3. C3 — Recently nothing
4. C4 — Nothing for several scans
Clock Conditions: Policy/Mechanism Separation

Default Policy:
1. C1 — Recently modified — ignore
2. C2 — Recently read only
3. C3 — Recently nothing
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Default Policy:

1. C1 — Recently modified — ignore
2. C2 — Recently read only — share/patch reference
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Alternative policies:
- Consider all pages for anything - insignificant excess saving
- Compression before patching - slightly less savings, less performance overhead.
SuperFastHash

- Hash table needs to fit in Xen’s limited memory (12M)
- \textit{Constant} 5 passes, hashing 1/5 of the range each time: 1.76M page sharing hash table size
Similarity Hash Table is also stored in Xen itself, statically allocated, sized $2^{18}$ unsigned longs (1MB).

- **Clearing:**
  - ⇒ At least after a full clock pass ($=5 \times$ partial) - allows finding similarity between keys from different passes.
  - ⇐ Early clearing reduces stale data (pages changed after indexing).
  - = Similarity Hash Table cleared each full clock pass.

- **Races:**
  - Locking only when building patch and replacing page.
  - Other races only result in larger patches.
Compression

- Compression postponed till after all pages are checked for similarity (prevents patching)
- Condition C4 used to identify a complete cycle of page sharing checks.
Swapping implemented in Dom0, where Xen defers all I/O.

- A thread for each guest to handle swap-in requests
- A thread (memory_monitor) tracks system mem

swapd may initiate swap-out when:

1. Mem exceeds HIGH_WATERMARK (till LOW_WATERMARK achieved)
2. Xen notifies via event channel, e.g. for share break
3. Process requests via IPC (XenStore), e.g. for VM cloning
Upon failure swapd continues silently:
- Full swap space
- No swap candidates

Implementation includes VM pausing. Actual swap file writing can happen asynchronously.
Paging: ioemu-swapd interaction

- Pages mapped by ioemu are ineligible for swapping out.
- Ioemu mapped pages are swapped in before accessed, if needed.
- Race prevented by blocking ioemu when swapping-in (using shared memory).
Default Evaluation Setup

- 4 cores (dual processor, dual core 2.33 GHz Intel Xeon)
- Page size 4K
- *How much memory?*
Using micro benchmarks.

<table>
<thead>
<tr>
<th>Function</th>
<th>Mean execution time ($\mu s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>share_pages</td>
<td>6.2</td>
</tr>
<tr>
<td>cow_break</td>
<td>25.1</td>
</tr>
<tr>
<td>compress_page</td>
<td>29.7</td>
</tr>
<tr>
<td>uncompressed</td>
<td>10.4</td>
</tr>
<tr>
<td>patch_page</td>
<td>338.1</td>
</tr>
<tr>
<td>unpatch</td>
<td>18.6</td>
</tr>
<tr>
<td>swap_out_page</td>
<td>48.9</td>
</tr>
<tr>
<td>swap_in_page</td>
<td>7151.6</td>
</tr>
</tbody>
</table>

Table 2: CPU overhead of different functions.

Swap-in may even take longer (swap file size, scheduling in Dom0,...)

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A good clock should give high lifetimes to compressed/patched pages, which are costly to access.

Performance of hetero workload close to homogeneous workload.

*Good performance?*
Isolated Mechanisms — Workload

- 4 steps:
  1. (1)-(2) Allocate pages (zero, random, identical, similar but not identical)
  2. (3)-(4) Read all pages
  3. (5)-(6) Make some small writes
  4. (7)-(8) Free mem and (9) exit
- After each step: pause and let memory stabilize (80 s).
- Each run is in a new VM.
- After each run the memory is allowed to stabilize.
- Each VM gets 256MB, of which 75% is filled.
- *How many concurrent VMs?*
Identical Pages

- With zero pages performance is similar.
- Reading invalidates condition C3 and C4, but not C2.
- Reads are free for sharing, otherwise performance is close.

Figure 5: Workload: Identical Pages. Performance with zero pages is very similar. All mechanisms exhibit similar gains.
Random Pages

None performs well, sharing is the worst.

Figure 6: Workload: Random Pages. None of the mechanisms perform very well, with sharing saving the least memory.
Pages 95% Similar to an Original Page

Sharing and compression do not take advantage of similarity (compared to random pages). Patching does.

Figure 7: Workload: Similar Pages with 95% similarity. Patching does significantly better than compression and sharing.
Hypervisor Settings for Real World Workloads

To enable comparison against VMware ESX:

- Limited to one CPU (2.3 GHz Intel Xeon) due to license.
- *How much memory?*
- Same Os images.
- ESX set to most aggressive configuration (10,000 \( \frac{\text{page}}{s} \)), DE configured similarly. *But according to Carl Waldspurger, ESX’s scan is capped at 500 \( \frac{\text{page}}{s} \) per VM!*
Homogeneous VMs: Xen vs. Xen+DE

Workloads: 1-6 VMs with 256MB.

- **More sharing opportunities expected**: PHP RUBiS on Debian. 2 client machines, each with 100 client sessions. Duration: 20 minutes.
- **Less sharing opportunities expected**: Linux kernel compilation.
Homogeneous VMs: Xen vs. Xen+DE

- RUBiS: Performance is unaffected, 60% of the memory is saved.
- Kernel: performance within 5%, 40% savings for 4 and more machines.
- Sharing is by design the largest memory saver.

![Graphs showing performance metrics]

Figure 8: Difference Engine performance with homogeneous VMs running RUBiS
Homogeneous VMs: Xen+DE, ESX

Workload: 4 VMs, each with 512MB. dbench for 10 minutes, 20 minutes stabilization.

In the end ESX catches up, but during operation DE performs 1.5 times better. *ESX finds more sharing opportunities!*

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Heterogeneous VMs: Xen+DE, ESX

Mixed-1: DE up to 45% better.

Mixed-2: DE X2 better.

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Heterogeneous VMs: Xen+DE, ESX Performance Overhead (for Mixed-1)

- Xen+DE over Xen: up to 7%.
- ESX with aggressive (*capped!*) page sharing over ESX without page sharing: 5%.

<table>
<thead>
<tr>
<th></th>
<th>Kernel Compile (sec)</th>
<th>Vim compile, Imbench (sec)</th>
<th>RUBiS requests</th>
<th>RUBiS response time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>670</td>
<td>620</td>
<td>3149</td>
<td>1280</td>
</tr>
<tr>
<td><strong>DE</strong></td>
<td>710</td>
<td>702</td>
<td>3130</td>
<td>1268</td>
</tr>
</tbody>
</table>

Table 3: Application performance under Difference Engine for the heterogeneous workload MIXED-1 is within 7% of the baseline.
Settings for Aggregate System Performance

- 4 cores
- 2.8GB free machine memory (excluding Dom0).
- 4 VMs and above, each allocated 650MB
- Workload: RUBiS (Java servlets implementation), 2 client machines
Aggregate Performance for Memory Over-Commit

- Xen: At 960 clients, 4 VMs use over 95% memory, some OS paging. 2 VMs with 1.2GB each do no better.
- Best DE: 6 VMs: manages 1.4 times the available memory
- Beyond 1400 clients: hypervisor paging (5000-20000 pages out, $\frac{1}{4}$ of it in)

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Conclusions

- Patching and in-memory compression can bring significant savings over sharing only.
- Difference Engine outperforms (a handicapped) VMware ESX by 1.6-2.5 for a similar performance overhead.

Future Work:

- DE mechanisms can improve a single OS memory management.
- Compress NRU shared pages.
- Protect against side channel attacks.