SmartMD: A High Performance Deduplication Engine with Mixed Pages

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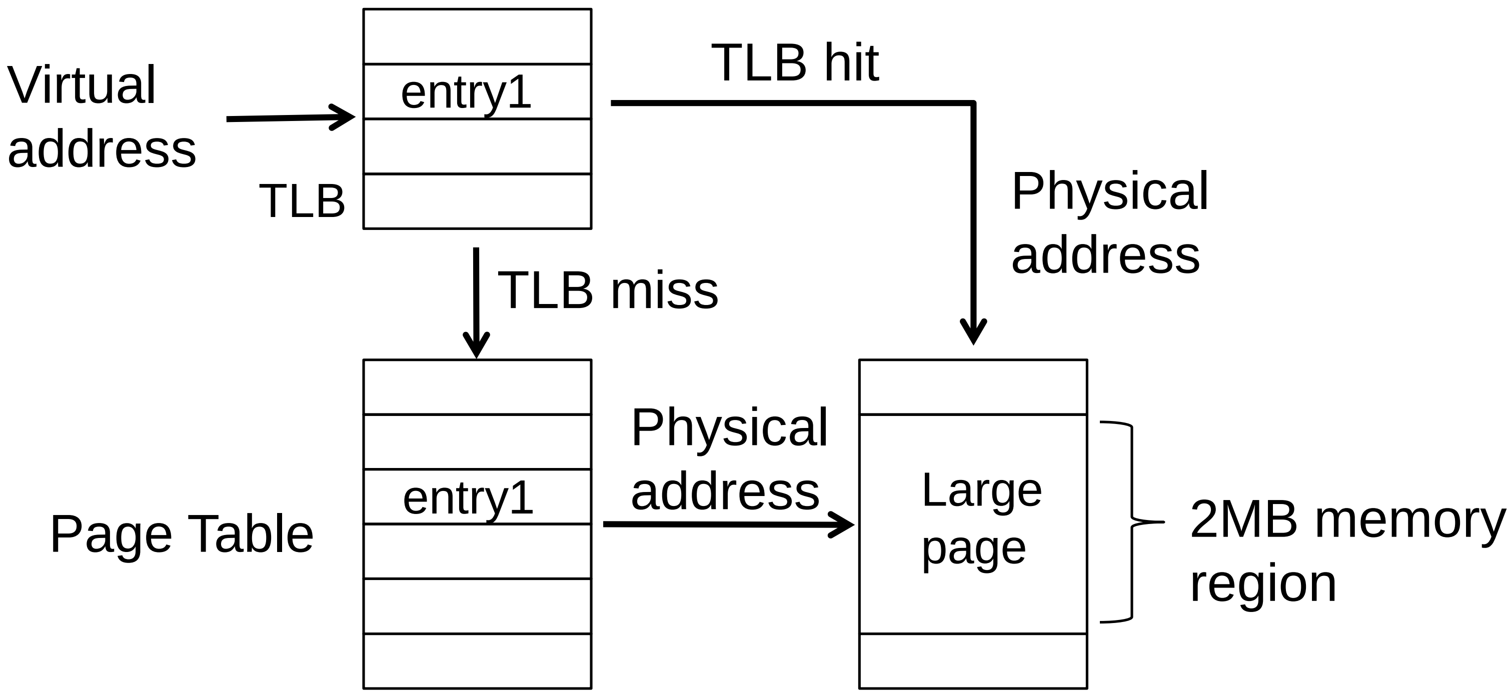
Overview

- **TLB (Translation Lookaside Buffer) miss** carries high penalty
  - Due to the access of page table
  - E.g., four level address mapping for x86-64 system with 4KB-page memory
- **Virtualization** increases TLB miss penalty
  - 2D page table walk (GVA -> GPA -> HPA)
  - Up to 24 memory references
- Uneven increase of TLB & memory size exacerbates the problem

Large Pages

- **Large pages** improve memory access performance
  - Fewer page table entries (1/512)
  - Larger TLB coverage



Benefits of Large Pages

- Performance improvement with large page
  - **Enabling large pages** in both guest and host can **improve memory access performance** by up to 68%

Benchmark	Host: Base Guest: Large	Host: Large Guest: Base	Host: Large Guest: Large
SPECjbb	1.06	1.12	1.30
Graph500	1.26	1.34	**1.68**
Liblinear	1.13	1.14	1.37
Sysbench	1.07	1.09	1.20
Biobench	1.02	1.18	1.37

Deduplication with Large Pages

- Redundant data is very common among VMs
  - Many base pages (4KB) share the same content
- **Large pages reduce the deduplication opportunerties**
  - Very few large pages (2MB) are exactly the same
  - ADA: aggressively split large pages into base pages

Policy	Benchmark	Memory Saving
Large Page w/o ADA	Graph500	0.37 GB(3.4%)
	SPECjbb2005	0.40 GB(5.9%)
	Liblinear	0.32 GB(2.0%)
	Sysbench	0.09 GB(0.8%)
	Biobench	0.20 GB(1.4%)
Large Page with ADA	Graph500	5.18 GB(47.9%)
	Specjbb2005	1.83GB(26.9%)
	Liblinear	3.79 GB (23.7%)
	Sysbench	2.83 GB(18.0%)
	Biobench	1.88 GB(13.7%)

Dedup. with **large pages (0.8% ~ 5.9%)**

Dedup. with **base pages (13.7% ~ 47.9%)**

Motivation

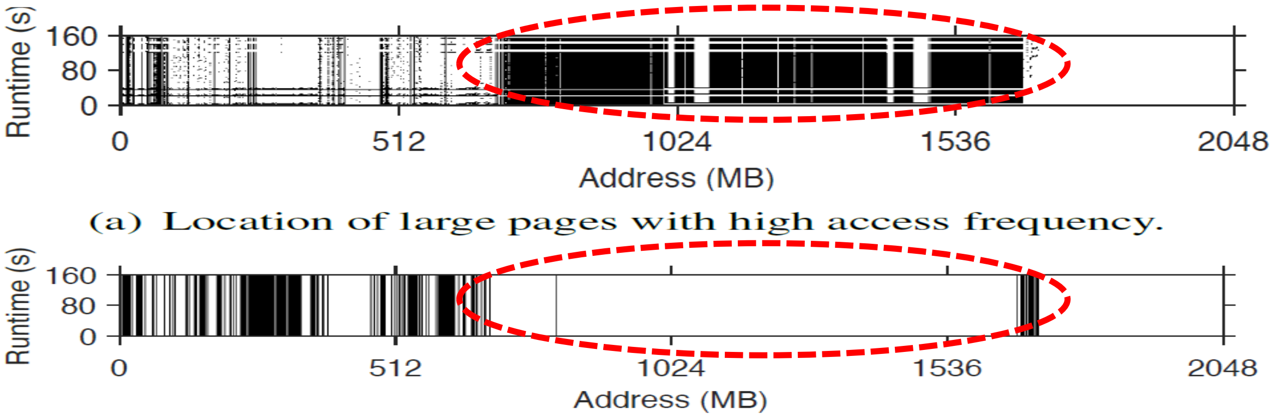
- Base pages vs. large pages
  - Exists a **tradeoff** between access performance and deduplication rate

	Access Performance	Deduplication Rate
Base pages (4KB)	Low	**High**
Large Pages (2MB)	**High**	Low

- **Question**: can we enjoy **both benefits** of high access performance and high deduplication rate simultaneously?

Our Solution

- **SmartMD**: an adaptive management scheme with mixed pages
  - **Monitors** page information (access frequency, repetition rate)
  - **Adaptively splits/reconstructs** large pages: manage with mixed pages
- **Observation**: many large pages have high access frequency but few duplicate subpages

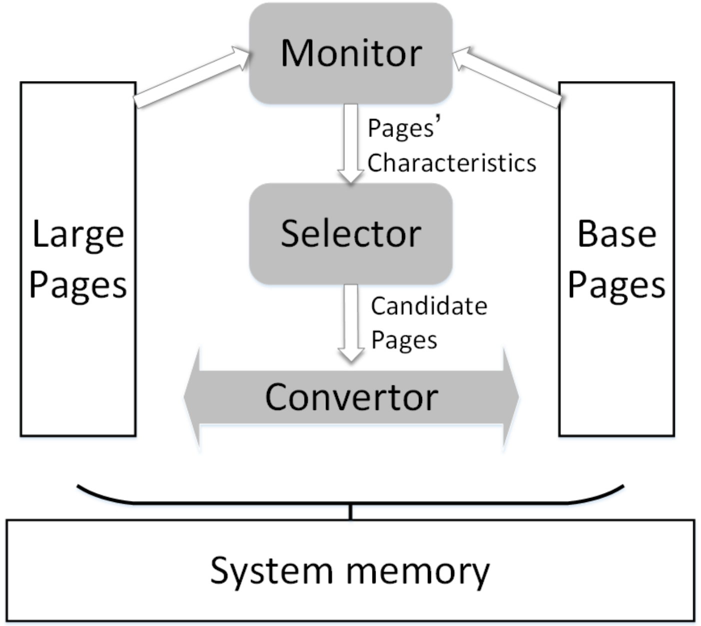


(a) Location of large pages with high access frequency.

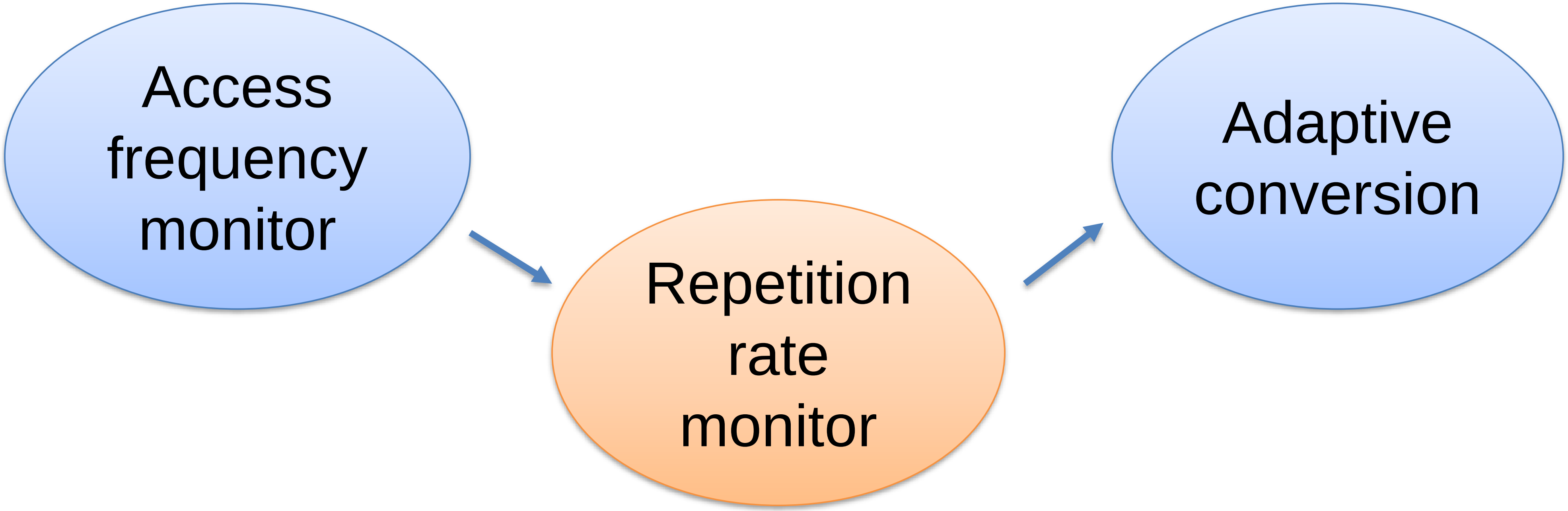
(b) Location of large pages with repetition rate higher than 1/8.

High-level Idea of SmartMD

- ➢Lightweight scheme to monitor page information
  - –Access frequency and repetition rate
- ➢Adaptive scheme to **selectively** split/reconstruct large pages
  - – **Split** into base pages
    - Cold pages with high repetition rate
    - For high deduplication rate
  - –**Keep** in large pages
    - Hot pages with low repetition rate
    - For high access performance
  - –**Reconstruct**: hot pages
    - For high access performance



Key Issues

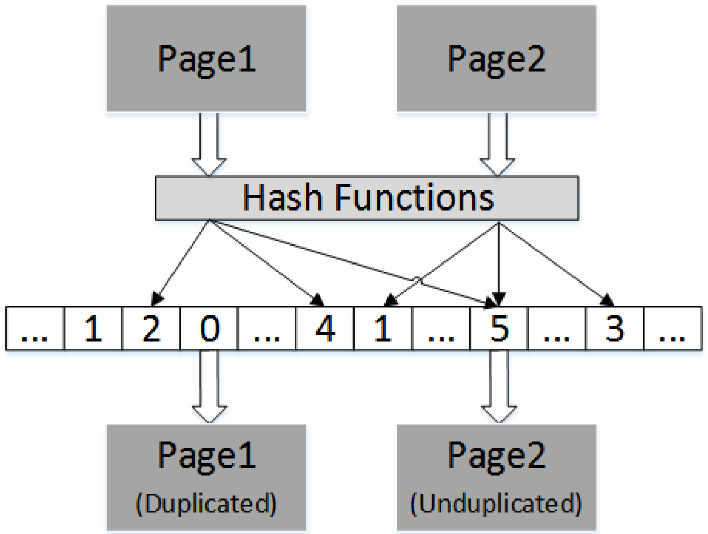

Access frequency monitor
Repetition rate monitor
Adaptive conversion

Monitor Access Frequency

- Scan pages periodically
- In each scan interval (e.g., 6s)
  - **Reset** the access bits of all pages
  - **Sleep** (e.g., 2.6s)
  - **Check** the access bits & update access frequency (+/- by one)
  - **Sleep** until this scan interval ends
- Use a counter to keep the access frequency of each large page

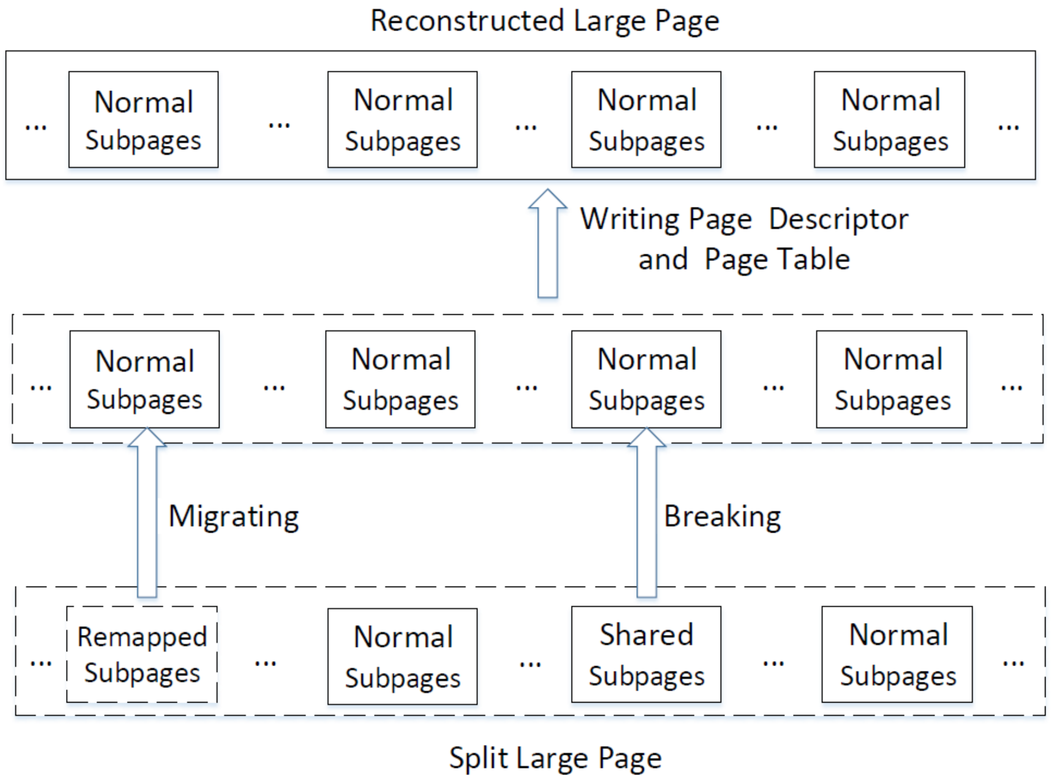
Monitor Repetition Rate

- ➢Scan pages periodically, and for each large page
  - Check each of its subpages and label it if it is a duplicate
  - Use a counter to record repetition rate
- ➢**Counting bloom filter**
  - # of entries: 8 # of base pages
  - Each entry: a 3-bit counter
  - 3 hash functions to index
- ➢**Sampling**
  - Sample only 25% subpages for pages being checked before and not being modified in last interval



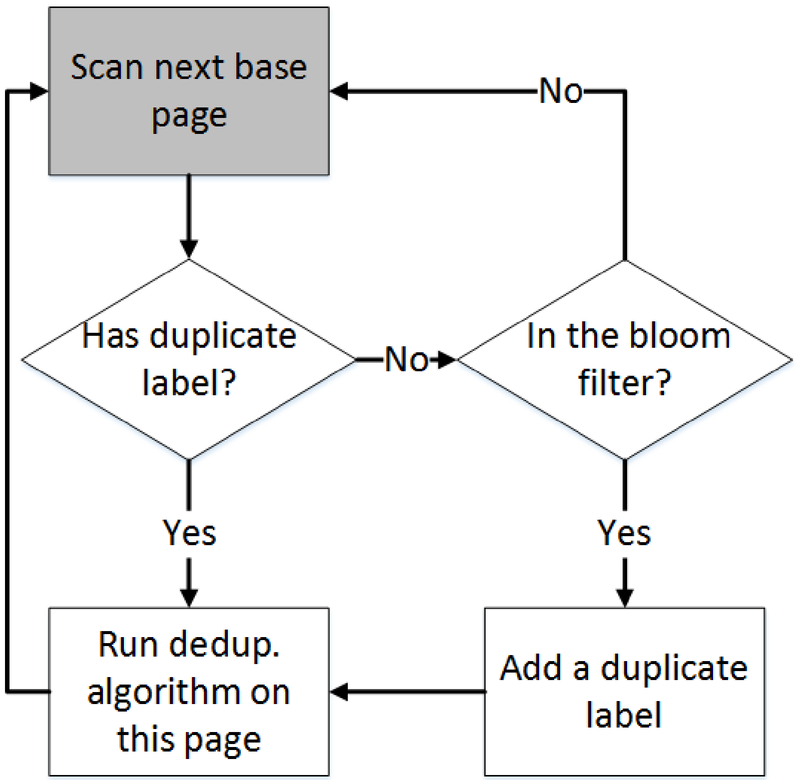
Adaptive Conversion

- Selectively split/reconstruct: **adjust** para. based on mem. util.
  - **Split**: Acc. Freq. < Thres_{cold} & Rep. Rate > Thres_{repet}
  - **Reconstruct**: Acc. Freq. > Thres_{hot}
- Implementation
  - Split: well supported by Linux
  - Reconstruct
    - **Gathering subpages**
      - Migrate remapped subpages
      - Break shared subpages
    - **Recreating page descriptor**
    - **Updating page table**



Deduplication

- Deduplication thread
  - Modify KSM's deduplication algorithm to merge duplicated pages
    - Two red-black trees to manage pages
  - With duplicate labels, **SmartMD improves deduplication efficiency**
    - Compare pages with duplicate labbels only
    - The # of candidate pages for comparison is reduced
    - The height of the red-black trees is reduced
    - The # of comparisons to merge a page is reduced



Evaluation

- Experiment setting
  - **Host**: two Intel Xeon E5-2650 v4 2.20GHz processors, 64GB RAM
  - **Guest**: QEMU&KVM. Boot up 4 VMs on one physical CPU, each VM is assigned one VCPU and 4GB RAM
  - Both guest and host OSes are Ubuntu 14.04
- Workloads and memory demands w/o deduplication

Graph-500	SPECjbb	Liblinear	Sysbench	Biobench
2.7GB	1.7GB	4.0GB	2.93GB	3.42GB

Overhead of SmartMD

- **SmartMD reduces CPU consumption** even if it requires more CPU cycles for monitoring
  - Average CPU utilization sampled in every second

	Monitor thread	Dedup thread	Total
KSM	0	33.5%	33.5%
Ingens	5.3%	21.3%	26.6%
SmartMD	13.1%	11.9%	25.0%

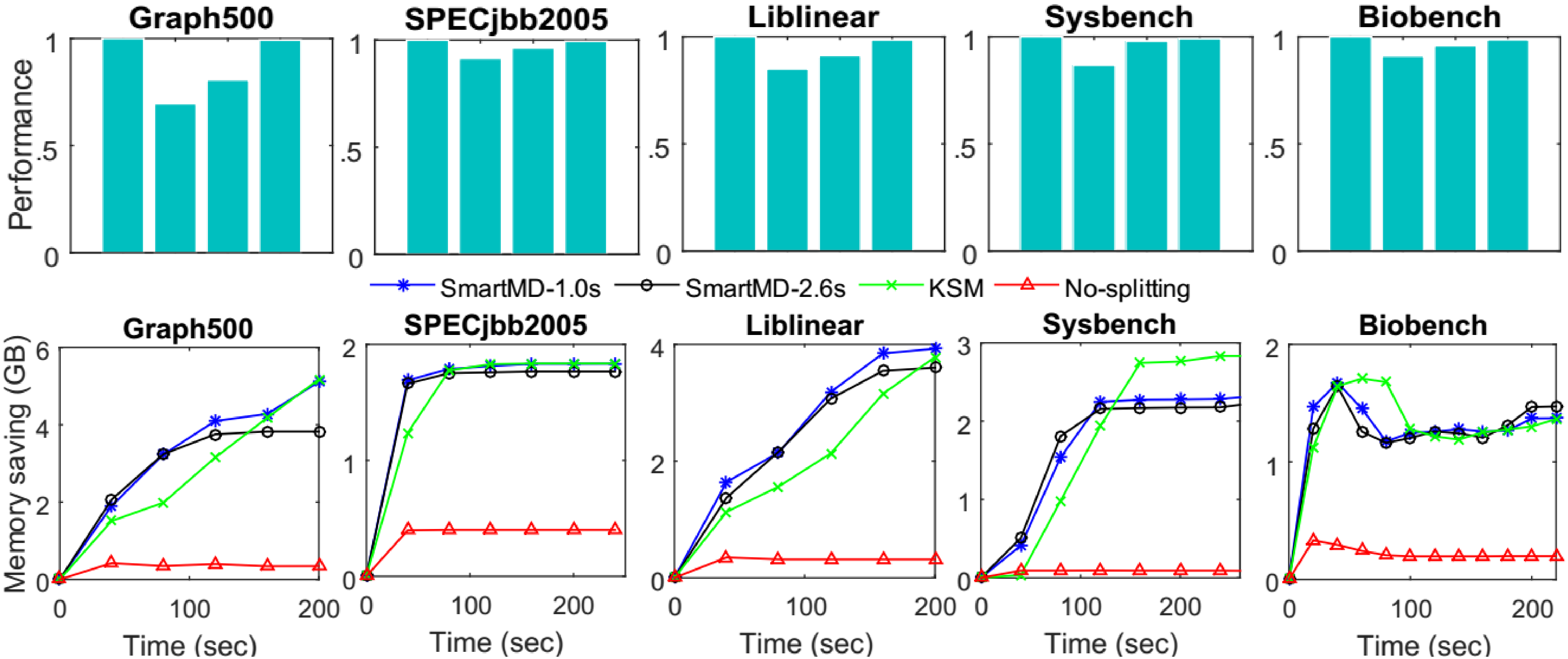
- **SmartMD introduces negligible memory overhead**
  - $3/2^{12}$ for storing counting bloom filter, and $1/2^{16}$ for keeping access frequency & repetition rate
  - Tens of MB for 16GB memory

Performance of SmartMD

- Comparison deduplication schemes
  - **KSM**: aggressively splits large pages which contain duplicate subpages
    - Already supported in Linux
    - **Achieves best memory saving**
  - **No-splitting**: deduplicates memory in unit of 2MB page
    - Without splitting any large page
    - **Achieves best access performance**
  - **Ingens** (OSDI'16): Splits large pages with low access frequency w/o considering repetition rate

Tradeoff

- KSM and no-splitting stand for two extreme points on the tradeoff curve (best performance vs. best memory saving)



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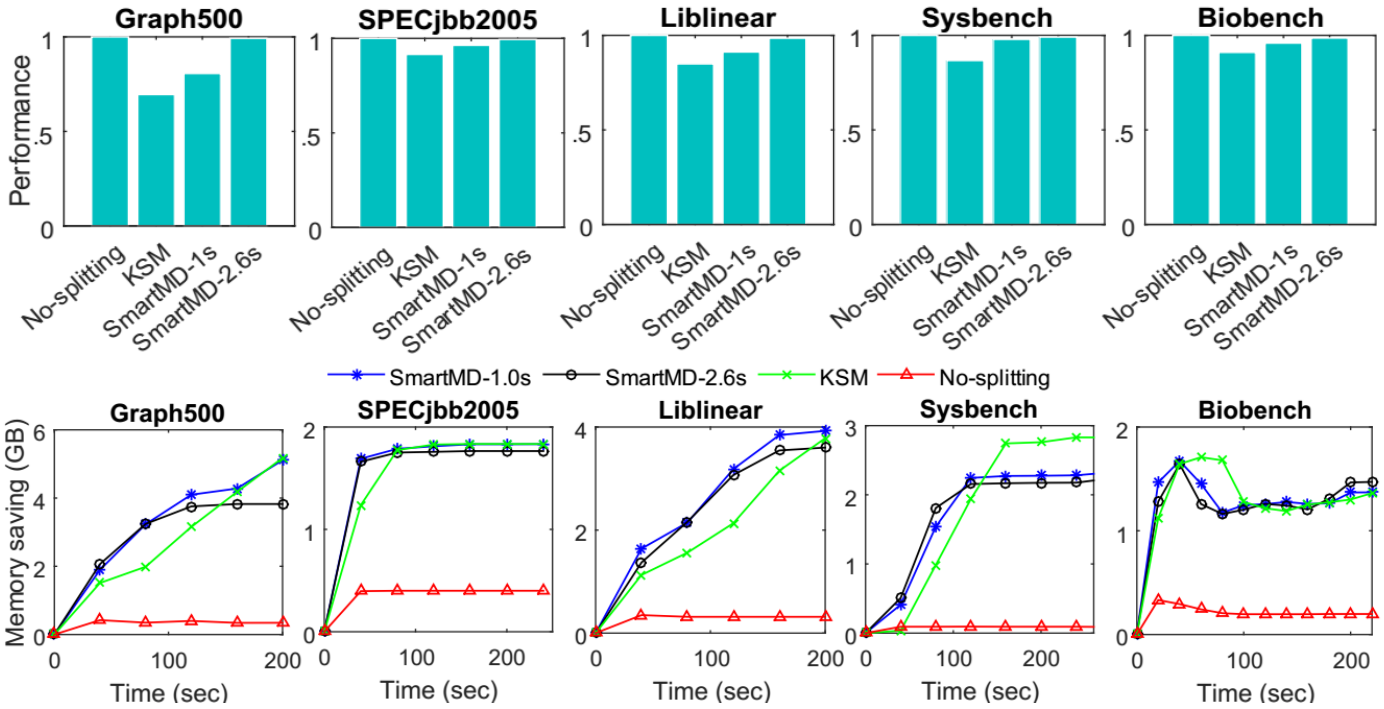


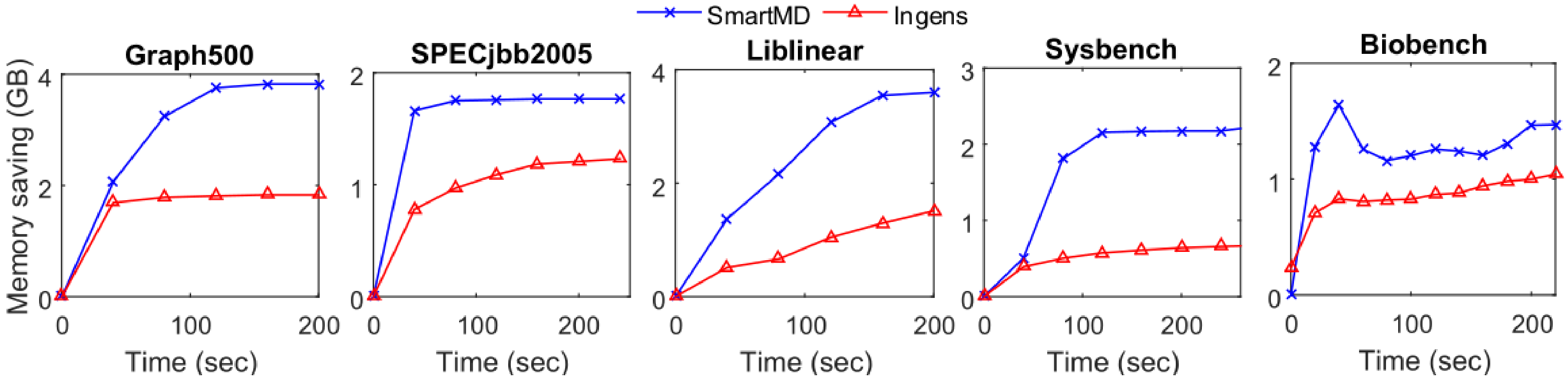
➢SmartMD achieves

- **similar performance with no-splitting**
- **similar memory saving with KSM**

➢**Takes both benefits simultaneously**

Comparison with Ingens

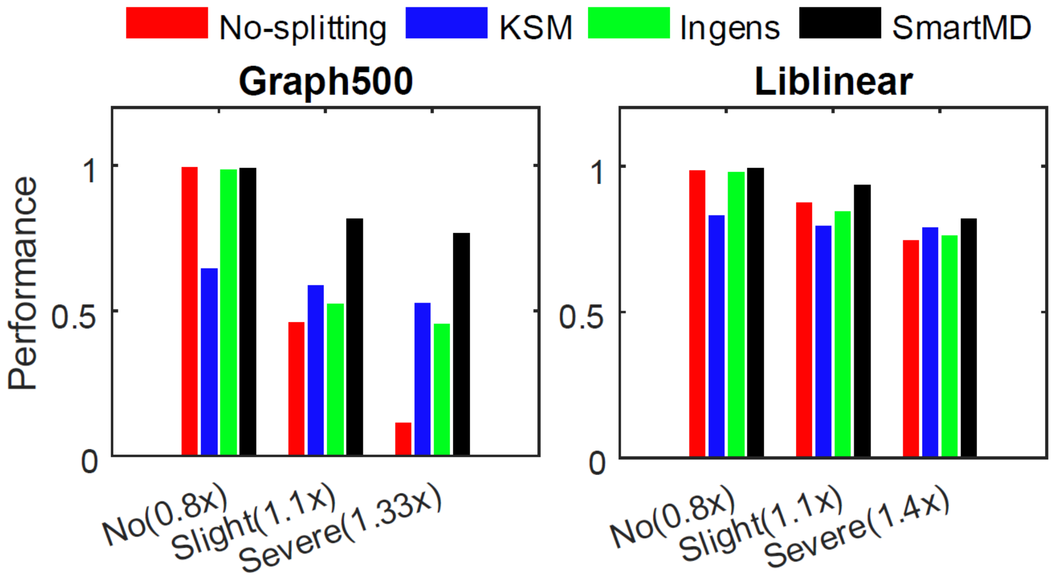
➢Memory saving



➢SmartMD can save 30% to 2.5x more memory than Ingens with similar access performance

Performance in Overcommitted Systems

- Overcommitment level (ratios of memory demand of all VMs to usable memory size): 0.8, 1.1, 1.4
  - Limit the host's memory by running an in-memory file system (hugetlbfs)



- **SmartMD achieves up to 38.6% of performance improvement over other schemes**

Performance on NUMA Machine

- Setting: 2 VMs on one physical CPU and two on a different CPU
  - Baseline: no-splitting (best access performance)

	Single-CPU	NUMA
Graph500	0.8%	1.6%
SPECjbb2005	0.6%	2.1%
Liblinear	0.9%	1.8%
Sysbench	1.1%	2.6%
Biobench	1.8%	3.9%

- **NUMA effect is very small**
  - The extra performance reduction on NUMA machine is **< 2%** comparing to Single-CPU

Conclusions

- ➢ **Tradeoff**: large pages improve memory access performance, but reduce deduplication opportunities
  - – Many pages have high access frequency but few duplicate subpages
- ➢ We propose **SmartMD, an adaptive scheme to manage memory with mixed pages**
  - – Split: cold pages with high repetition rate
  - – Reconstruct: hot pages
  - – SmartMD simultaneously takes both benefits
    - High memory performance (by accessing with large pages)
    - High memory saving (by deduplcating with base pages)

Thanks!

Q&A