

# Towards Improved Provisioning and Utilization of Resources in Virtualized Environments

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# Computing-as-a-Service: The New Norm



Electricity Grid



Public Transport



Virtualization  
Containers  
Serverless Computing  
Edge Computing

Enabling technology

- Software as a Service
- Platform as a Service
- Infrastructure as a Service

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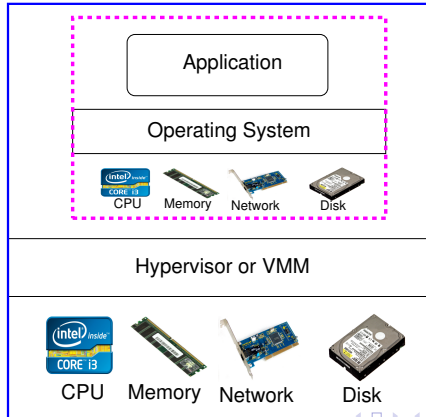
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# Thesis Scope

## Two types of resources in virtualized environment

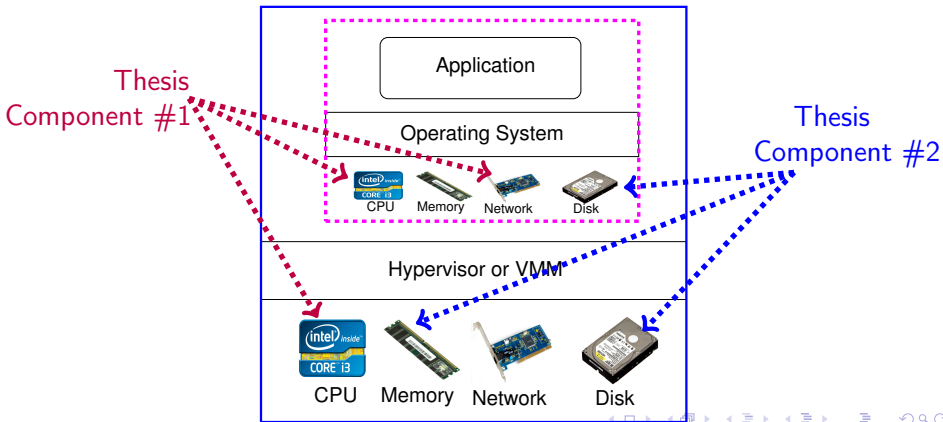
- 1 Resources allocated to virtual machines
- 2 Resources available to host for virtualization operation & overheads



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## Two types of resources in virtualized environment

- 1 Resources allocated to virtual machines
- 2 Resources available to host for virtualization operation & overheads



# Thesis Contributions and Deliverables

## Contribution 1: Network-affinity aware CPU Usage Estimation

- *Initial Attempt*: Regression model to predict “total” CPU requirement
- *Challenge*: Maximum error 6% absolute CPU
- *How Overcame*: Predict “differential” CPU usage—Max error 2%

# Thesis Contributions and Deliverables

## Contribution 1: Network-affinity aware CPU Usage Estimation

## Contribution 2: VM Disk I/O Reduction by Host-cache Manipulation

- *Initial Attempt:* Performing variable-sized deduplication
- *Challenge 1:* Real-world I/O trace available only for fixed-size
- *Alternative:* Show value of caching hints in fixed-size dedup
- *Challenge 2:* Real system not amenable to repeatability & instrumentation
- *Alternative:* Build custom simulator for evaluation
- *Challenge 3:* More traces needed for evaluation
- *Alternative:* Build I/O tracing kit
- *Challenge 4:* Unable to deploy I/O tracing tool on department servers
- *Alternative:* Survey and make case for trace generation

# Thesis Contributions and Deliverables

Contribution 1: Network-affinity aware CPU Usage Estimation

Contribution 2: VM Disk I/O Reduction by Host-cache Manipulation

## Tools and Deliverables

- 1 WLoadGen: A load generator for CPU, disk & network loads
- 2 SimReplay: A simulator for analyzing host cache effectiveness
- 3 preadwritedump: A kernel module for I/O request tracing



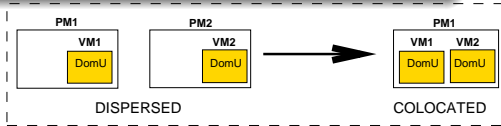
# Content Outline (Part I)

## Affinity-aware CPU usage estimation in *migratory* VM scenarios

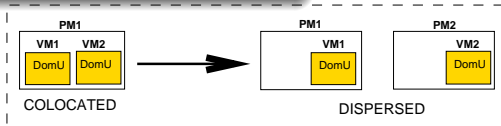
- 1 **Profiling study** of Xen network virtualization to show the different flow paths for *intra-PM* and *inter-PM* network traffic
- 2 **Benchmarking** of CPU usage for various workloads in colocated and dispersed scenarios (demonstrated to be linear)
- 3 Pair-wise linear regression model to **predict total** CPU when network traffic changes nature between intra-PM and inter-PM
- 4 Pair-wise linear regression model to **predict differential** CPU usage
- 5 Application of pair-wise models to predict for **multi-VM scenarios**

# Migration-Enabled Resource/Performance Management

## Consolidate/colocate VMs for Resource Efficiency

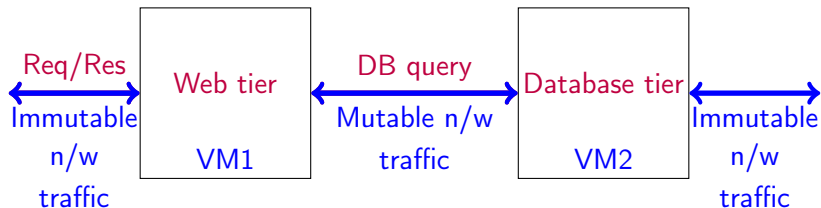


## De-consolidate/disperse VMs for QoS



- Both colocation and dispersion need **resource usage estimation**
- Incorrect estimation is sub-optimal
  - Under-estimation => degraded performance
  - Over-estimation => wasted resources

# Mutable and Immutable Network traffic for *Migratory* VMs



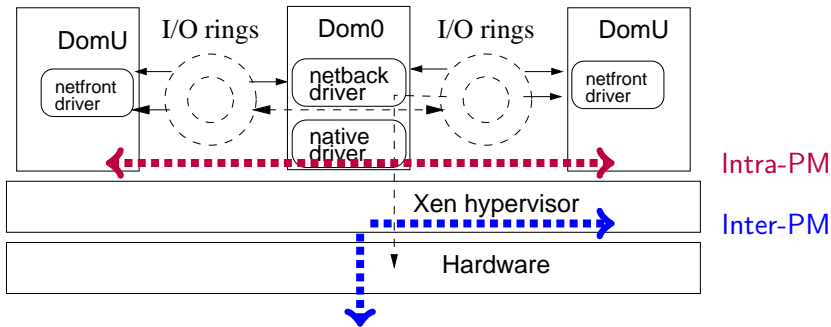
## Mutable n/w traffic

Network traffic between VMs whose relative placement may *change between colocated and dispersed*, due to server consolidation strategies

## Our hypothesis

Mutable network traffic has *different CPU overheads* in colocated and dispersed scenarios => ignoring affinity effects could result in incorrect CPU usage estimation

# Communicating VMs (Xen-view)

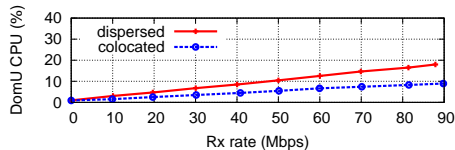


- **Dom0 overhead** for DomU's I/O activity (network & disk)
- Intra-PM network traffic
  - Dom0 does not use native I/O drivers
  - Shared memory based copying of packets
- **Less CPU overhead for intra-PM** traffic compared to *inter-PM*
- Needs to be accounted for during VM migration

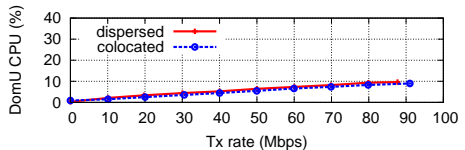
# Benchmarking: Effect of colocation on CPU usage for *Mutable* N/w traffic

**Benchmarking setup:** 2 VMs on 2 PMs—dispersed and colocated scenarios

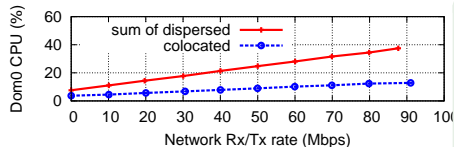
**Network load:** Transmitted (Tx) by one VM and Received (Rx) by other



(a) Receiving DomU CPU util



(b) Transmitting DomU CPU util



(c) Dom0 CPU util for Rx/Tx

## Observations

- **DomU:** Rx increase from 20-90 Mbps => decrease of 2-8% CPU util
- **Dom0:** Increase from 20-90 Mbps => decrease of 9-25% CPU util

# Benchmarking: Effect of colocation on CPU usage for Immutable n/w traffic, CPU and disk loads

Benchmarking setup: 4 VMs on 4 PMs—dispersed and colocated scenarios

Table : Percentage CPU usage for Immutable Rx

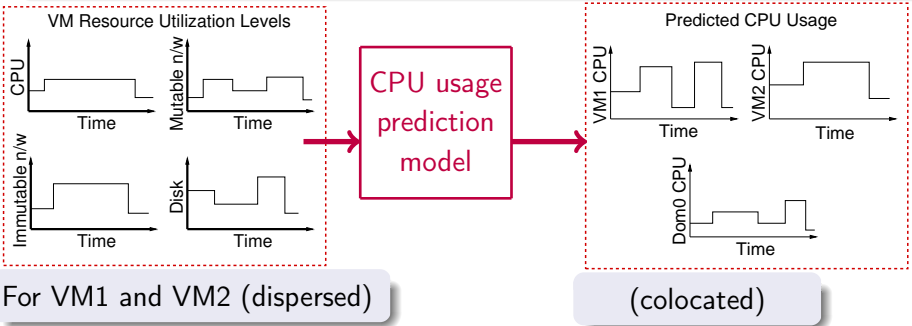
Immutable Rx (Mbps) ( $< VM_1, VM_2 >$ )	% CPU utilization	
	Dispersed case $VM_1, VM_2, \sum Dom0_i$	Colocated case $VM_1, VM_2, Dom0$
$<20, 50>$	4, 7, <b>18</b>	4, 7, <b>14</b>
$<40, 10>$	<b>6, 2</b> , 15	<b>6, 2</b> , 11
$<60, 10>$	8, 2, 18	8, 2, 14

## Observations

- 1 No change in DomU CPU usage between colocated and dispersed
- 2 Dom0 CPU usage change of **4% for extra Dom0 instance (constant)**
- 3 Similar observations for other workloads—CPU and disk read/write

# Problem: Affinity-aware Resource Requirement Estimation

Given a pair of VMs and their resource utilization levels, predict the CPU resource requirement of DomU & Dom0, when VM placement scenario changes between dispersed and colocated.



## Core Idea

Since correlation of CPU usage with all other resources usage is linear, build **linear prediction models**

# Linear Regression Modeling for CPU Estimation

## Parameters in the models

- **CPU** metrics: user, system, iowait
- **Disk** metrics: read blocks/second, write blocks/second
- **Mutable and immutable** network metrics: Rx and Tx Kbps

## DomU Models

$$CPU_{colocated} = f(CPU, Disk, Mutable, Immutable)_{dispersed}$$

$$CPU_{dispersed} = f(CPU, Disk, Mutable, Immutable)_{colocated}$$

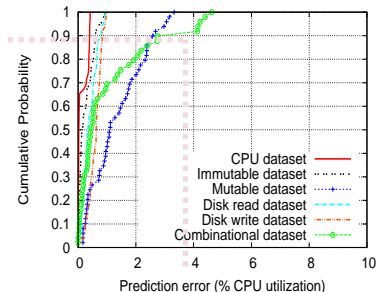
## Dom0 Models

$$CPU_{colocated} = f(CPU_1, Disk_1, Mutable_1, Immutable_1, \\ CPU_2, Disk_2, Mutable_2, Immutable_2)_{dispersed}$$

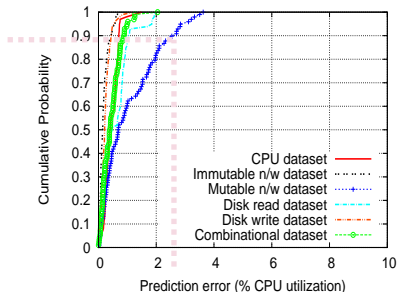
$$CPU_{dispersed} = f(CPU_1, Disk_1, Mutable_1, Immutable_1)_{colocated}$$



# Prediction for Synthetic workloads - Xen Dom0 model



(a) Dispersed to colocated

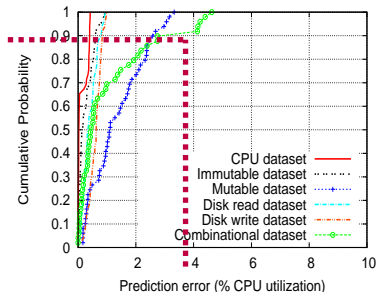


(b) Colocated to dispersed

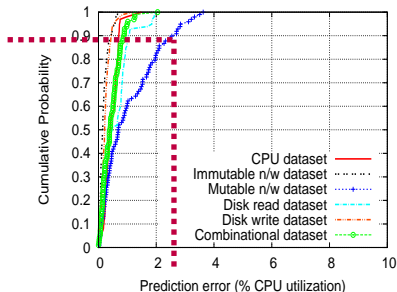
## Observations

90<sup>th</sup> percentile prediction error within 3% absolute CPU utilization, and maximum error 5-6% absolute CPU (Similarly for RUBiS workload as well)

# Prediction for Synthetic workloads - Xen Dom0 model



(a) Dispersed to colocated



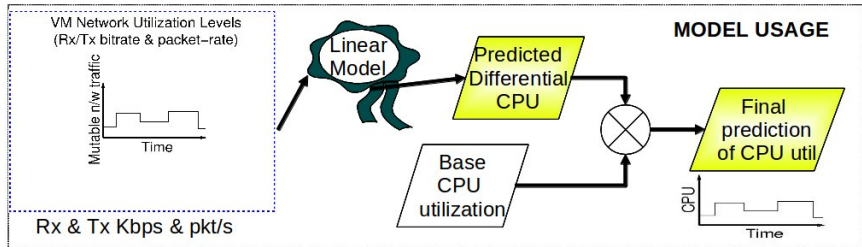
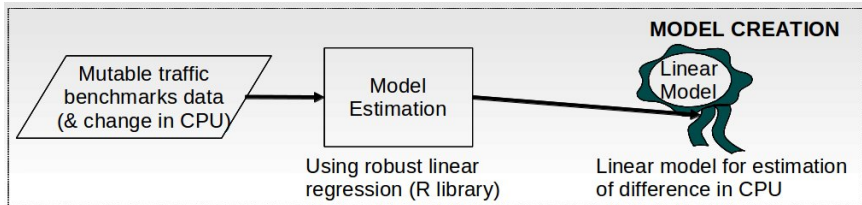
(b) Colocated to dispersed

## Observations

90<sup>th</sup> percentile prediction error within 3% absolute CPU utilization, and maximum error 5-6% absolute CPU (Similarly for RUBiS workload as well)

# Building an Enhanced Prediction Model

Because “differential” CPU usage is only due to mutable n/w traffic



# Evaluation of Differential CPU Prediction Models

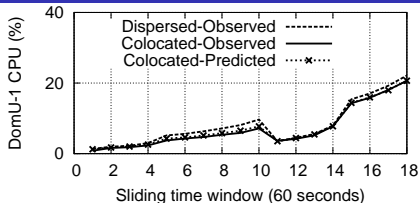


Figure : Colocated DomU-1 (Synthetic)

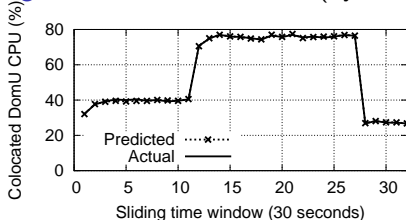


Figure : Colocated DomU-1 (RUBiS)

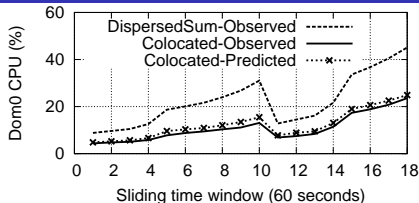


Figure : Colocated Dom0 (Synthetic)

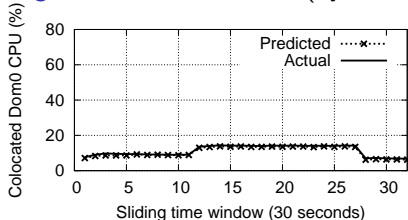


Figure : Colocated Dom0 (RUBiS)

## Result

Maximum prediction error between 1-2% absolute CPU utilization.

# Applying Pair-wise Models to Multi-VM Scenarios

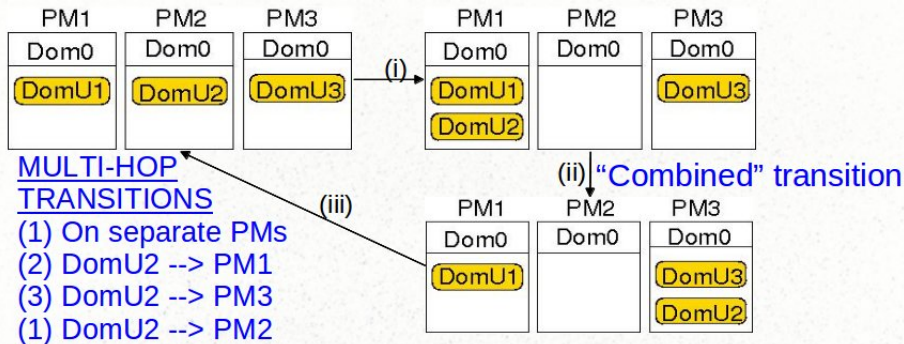


Table : Maximum error in Dom0 CPU utilization prediction

Transition	Max error (% absolute CPU)		
	Dom0-PM1	Dom0-PM2	Dom0-PM3
Transition (i)	0.75	-	-
Transition (ii)	1.99	-	0.85
Transition (iii)	-	0.51	0.43

# Summary of Part I

- **Colocation of mutually-communicating VMs impacts their CPU requirement**
  - **DomU:** For Rx, increase from 20 to 90 Mbps => decrease from 2% to 8% CPU requirement
  - **Dom0:** Increase from 20 to 90 Mbps => decrease from 9% to 25% CPU requirement
- **Simple linear model shown to predict “differential” CPU requirement from mutable n/w traffic profiles**
  - **Synthetic workloads:** Max error within 1.5% absolute CPU utilization for both DomU and Dom0 models
  - **RUBiS benchmark application:** Max error within 1.5% for Web and DB tiers, and Dom0
  - **Multi-VM scenario:** Max error within 2% for all transitions

# Content Outline (Part II)

## Part II. Host cache usage optimization for virtualized services

- 1 Analysis of existing work (IODEDUP) to show inconsistent performance
- 2 Redirection of I/O requests from within the virtual machines
- 3 To implicitly manipulate host cache in content-deduplicated fashion
- 4 Using implicit caching hints
- 5 Evaluation using public dataset available online
- 6 Case for generation of realistic I/O deduplication benchmarks

# Effect of Data Similarity on Host-cache Effectiveness

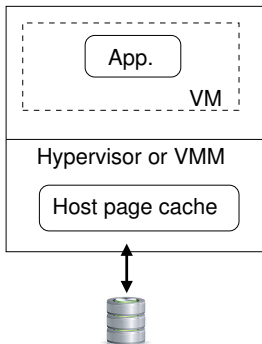


Figure : Typical virtualized system

## Two optimization avenues

- 1 Duplicate I/O
- 2 Duplicate content in cache

## Two orthogonal solutions

- 1 I/O deduplication (IODEDUP[1]) :  
but causes **cache inclusiveness problem**
- 2 Memory deduplication (Satori[2]) :  
dedupes **after** data is fetched

## Sources of data similarity

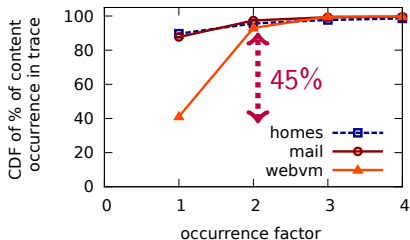
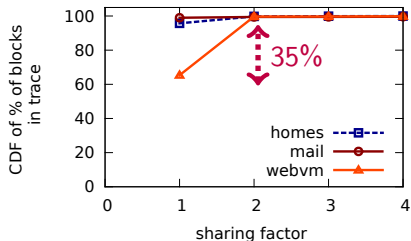
Similar operating systems,  
libraries, binaries, file copies,  
etc.

## Aim of this work

Improve host-cache effectiveness *using*  
I/O deduplication techniques,  
i.e., **achieve both** in one stroke.



# Traces<sup>1</sup> used for evaluation: Similarity study



## Observations

- *homes* & *mail* traces have 95% blocks with sharing factor 1, whereas *webvm* trace has 35% blocks with sharing factor 2
- In *webvm* trace, 45% content occur twice, compared to 6-10% in *homes* and *mail* traces

## Conclusions

*webvm* trace is likely to benefit the most from I/O deduplication

<sup>1</sup>Workload traces borrowed from the IODEDUP paper [1]. Traces available online at [3] and SNIA

# Existing<sup>2</sup> I/O deduplication technique: IODEDUP<sup>3</sup>

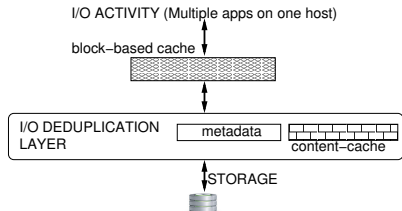


Figure : System Architecture of IODEDUP

## Functioning

- Creates and maintains content-based cache
- Intercepts read requests & services without accessing disk if possible

<sup>2</sup>Other related work for I/O deduplication & reduction discussed in thesis.

<sup>3</sup>*I/O Deduplication: Utilizing Content Similarity to Improve I/O Performance*

# Existing<sup>2</sup> I/O deduplication technique: IODEDUP<sup>3</sup>

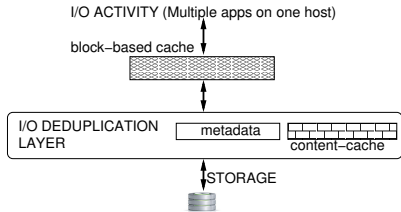


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## Drawbacks

- Content-cache *sizing* needs exploration
- Block-cache still faces *duplicate content* problem

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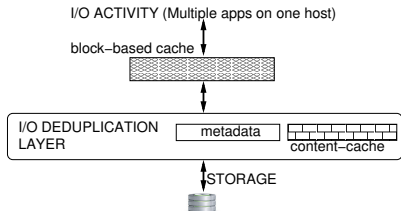


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## Drawbacks

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## Functioning

- Creates and maintains content-based cache
- Intercepts read requests & services without accessing disk if possible

## Our contribution

- Perform *study of cache effectiveness* for IODEDUP system, using a custom simulator

<sup>2</sup>Other related work for I/O deduplication & reduction discussed in thesis.

<sup>3</sup>*I/O Deduplication: Utilizing Content Similarity to Improve I/O Performance*

# Study of cache effectiveness for IODEDUP

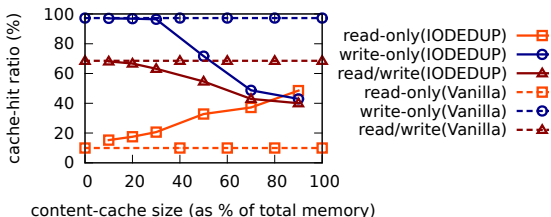


Figure : Cache-hit ratios for IODEDUP for *webvm* trace. Total cache 512 MB

## Observations

- 1 Read-only trace has lowest performance at content-cache of 10% & highest at 90%
- 2 Write-only performance varies reverse, i.e., highest at 10% and lowest at 90%
- 3 At content-cache setting of 90%, read-only performance is  $4\times$  Vanilla, but read/write performance 42% worse than Vanilla.

## Conclusion

**Inconsistency** in achievable cache effectiveness

# Fundamental issues preventing efficient I/O reduction

## Issues

- 1 IOEDUP system [1] has cache inclusiveness problem
- 2 Memory deduplication [2] works after data is already fetched from disk

## Naive solution

- Operate host cache in fully-deduplicated fashion, such that only data not present in cache will ever be fetched from disk

## Challenges in implementing naive solution

- 1 Needs change to cache datastructures and/or algorithms
- 2 Needs metadata updates per cache insertion
- 3 Needs invasive monitoring & metadata updates per cache eviction

# DRIVE: Using implicit caching hints to achieve disk I/O reduction in virtualized environments

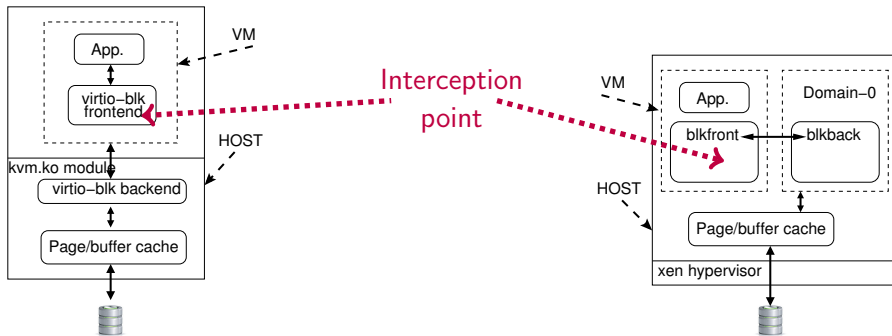
## Our Approach

- Augment the virtual disk driver to **use implicit caching hints** to achieve an approximately fully-deduplicated host cache

## System Requirements for DRIVE

- ① Intercept block read *request* path for **metadata lookup** and I/O redirection, if present
- ② Intercept block read *return* path for **metadata update**, if not previously present
- ③ Intercept block write *request* path for **metadata invalidation**
- ④ Maintain **implicit caching hints** within metadata to aid efficient I/O redirection.

# Block request interception-point for DRIVE



(a) KVM split-driver architecture

(b) Xen split-driver architecture

## Interception within VM's front-end driver

- **De-coupling** of the front-end and back-end drivers enables simple I/O redirection
- Results in **implicit** manipulation of host-cache as a content-deduplicated cache
- Exploits individual workload's **content self-similarity**, useful irrespective of co-hosted VMs
- Implementation within generic `virtio` drivers **obviates dependence** on VMM & guest OS



# DRIVE metadata store: semantics and usage

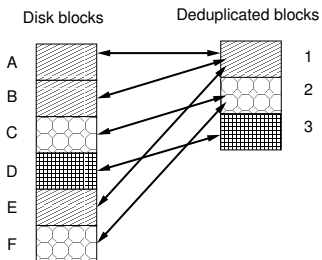


Figure : Semantics of metadata store.

# DRIVE metadata store: semantics and usage

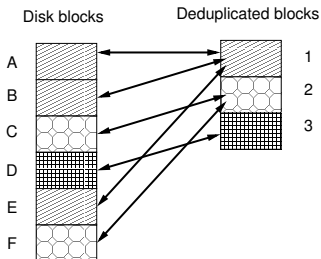


Figure : Semantics of metadata store.

## Obtaining and using hints for I/O redirection

- 1 When a block is fetched, it is "known" to be **cached**
- 2 Above is noted in metadata, **marked as leader**
- 3 For next redirection, **leader is used**

# DRIVE metadata store: semantics and usage

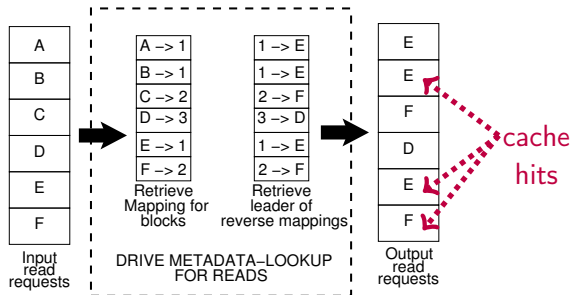
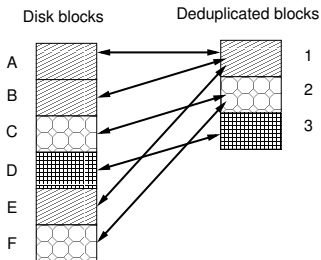


Figure : Semantics of metadata store.

Figure : Example of read request redirection in DRIVE

## Obtaining and using hints for I/O redirection

- 1 When a block is fetched, it is "known" to be **cached**
- 2 Above is noted in metadata, **marked as leader**
- 3 For next redirection, **leader is used**

# Evaluating host-cache effectiveness in DRIVE system

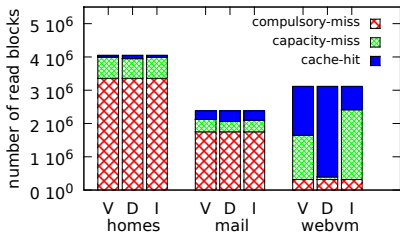


Figure : Classification of read responses

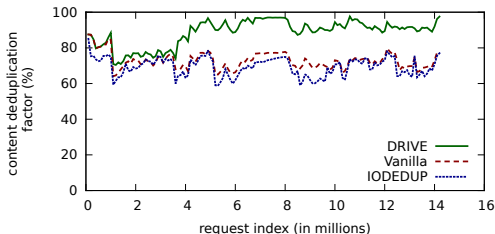


Figure : Content deduplication factor of page cache upon *webvm* trace.

## Conclusions

- Both *homes* and *mail* workloads have huge number of compulsory misses, whereas the *webvm* workload has significantly fewer.
- DRIVE decreases number of capacity misses to 5% of Vanilla
- DRIVE achieves up to 97% deduplication in block-cache

# Identifying similarity in multiple virtual machines

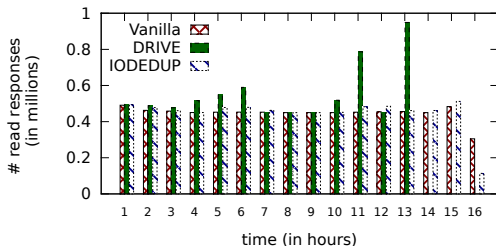


Figure : Read response throughput for aggregated (*homes+webvm*) trace.

Table : Performance for aggregated trace replay

Scheme	Cache-hit ratio (%)	Disk reads reduced(%)	Avg. read response latency (msec)
Vanilla	61.2	1.6	7.9
DRIVE	67.6	18.5	6.5
IOEDUP	62.4	4.3	7.7

## Conclusions

- DRIVE completes earlier due to higher number of responses per hour on average<sup>4</sup>.
- Huge margin in percentage of disk reads reduced

## Summary of DRIVE

- 1 Performs implicit caching hint-based I/O redirection
- 2 Simulation-based evaluation shows promise—up to 97% content-deduplicated cache achieved
- 3 Further analysis requires more production traces

<sup>4</sup>Throughput derived from measured cache-hits & disk-reads and assumed latency values.



# Literature survey for “realistic” dataset generation

## Types of datasets generated

- 1 I/O traces (without content) [4, 5, 6, 7, 8]
- 2 Filesystem content (without I/O traces) [9]

## Relevant characteristics for I/O traces<sup>5</sup>

Block accessed distribution & Jump distances—*spatial locality*  
Run lengths & Block reuse distances—*temporal locality*

## General approach

- 1 Capture Multi-dimensional distributions and/or Markov models
- 2 Use above captured models to create new traces with similar properties
- 3 Vary appropriate parameters to create different traces as necessary

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<sup>5</sup>*webvm* and *homes* trace characterization presented in thesis.

# Content-defined characterization of *webvm* trace

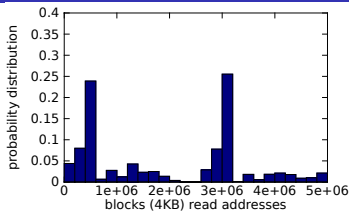


Figure : (a) Block access distribution

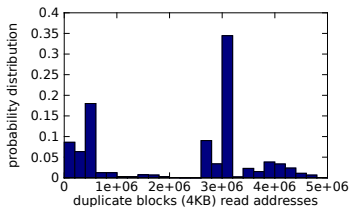


Figure : (b) Duplicate block distrib

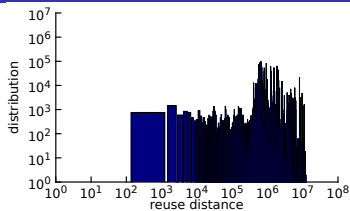


Figure : (c) Block reuse distribution

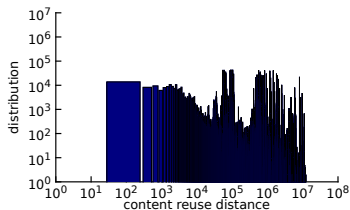


Figure : (d) Content reuse distribution

## Observations

- Even duplicate content access has **spatial locality** property
- **Temporal locality** is higher for content than block



# DRIVE system summary & conclusions

- In this component, we addressed I/O reduction via deduplication
- We analyzed existing work (IODEDUP) and showed that its performance is inconsistent depending on the read/write request-mix of the workload.
- We presented design & implementation of our DRIVE system
- Simulation evaluation shows promise—achieves 97% content deduplication of the host cache.
- We concluded with a survey of publicly available datasets, as well as benchmark generation literature, to make the case that future work towards I/O deduplication benchmarks is necessary

# Bibliography I



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