Virtualization – Part III
VMware

Ahmad Ibrahim

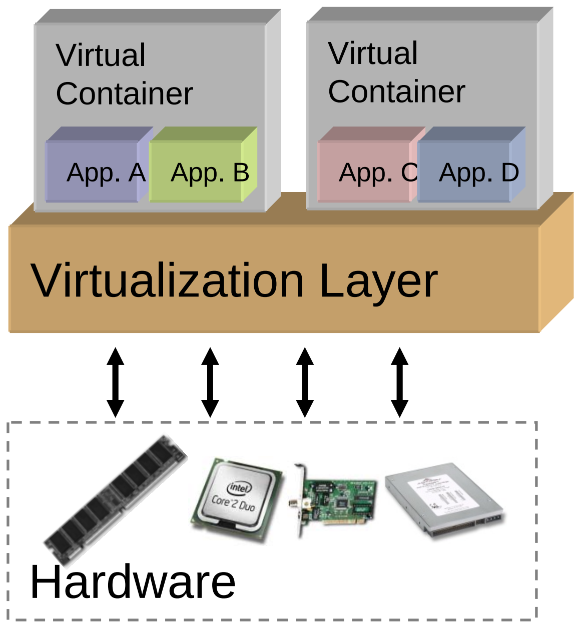
Topics Covered – My Cheat Sheet

- Virtualization
  - Review
  - What is virtualization
  - Definition of classical virtualization
  - Trap-and-Emulate
  - Memory Management
- x86 Virtualization
  - What are the challenges
    - Memory Tricks
  - What are the solutions
    - Binary Translation
- Approaches to Server Virtualization
  - Full Virtualization
  - Paravirtualization OS Assisted virtualization
  - Hardware-assisted virtualization
  - Charts
- Memory Management
  - Memory Tax
  - Chart
  - Ballooning
  - Content based Page Sharing

Overview

- Virtualization
- x86 Virtualization
- Approaches to Server Virtualization
- Memory Resource Management Techniques

What is Virtualization?



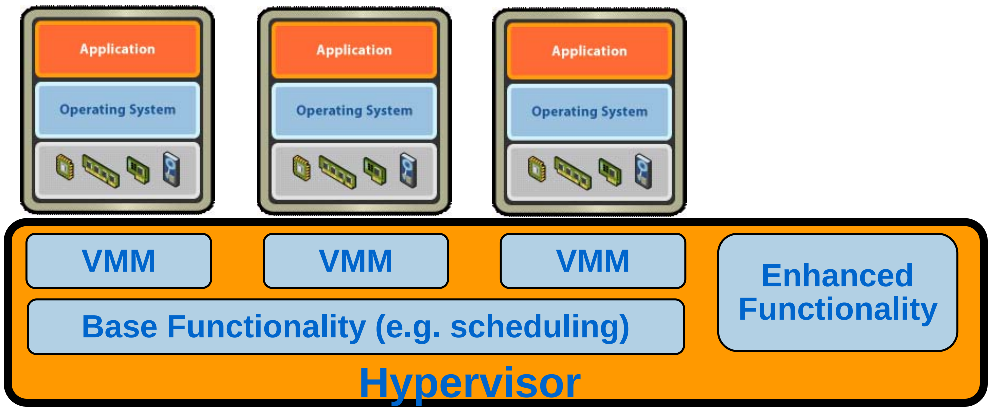
- Virtualization allows one computer to do the job of multiple computers, by sharing the resources of a single hardware across multiple environments

VMWare Product Suite

- Desktop – runs in a host OS
  - VMWare Workstation (1999) – runs on PC
  - VMWare Fusion – runs on Mac OS X
  - VMWare Player – run, but not create images
- Server
  - VMWare Server (GSX Server) –hosted on Linux or Windows
  - VMWare ESX (ESX Server) – no host OS
  - VMWare ESXi (ESX 3i) – freeware (July 2008)

Terminology

- Virtual Machine
  - abstracted isolated Operating System
- Virtual Machine Monitor (VMM)
  - capable of virtualizing all hardware resources, processors, memory, storage, and peripherals
  - aka Hypervisor

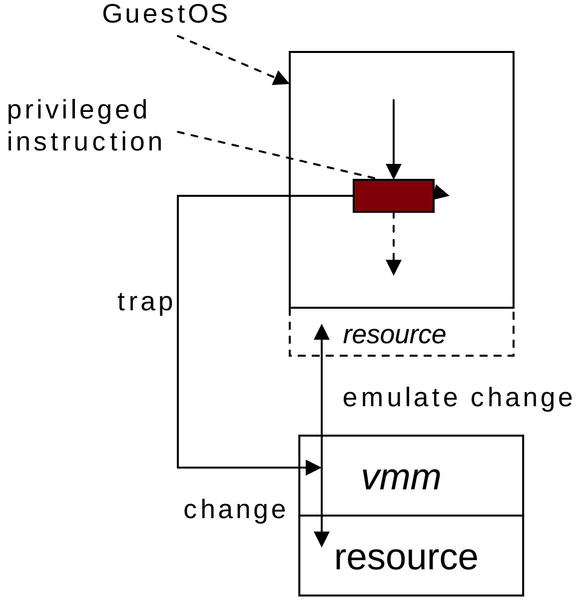


Popek & Goldberg: Virtualization Criteria

- "*Formal Requirements for Virtualizable Third Generation Architectures*" (1974)

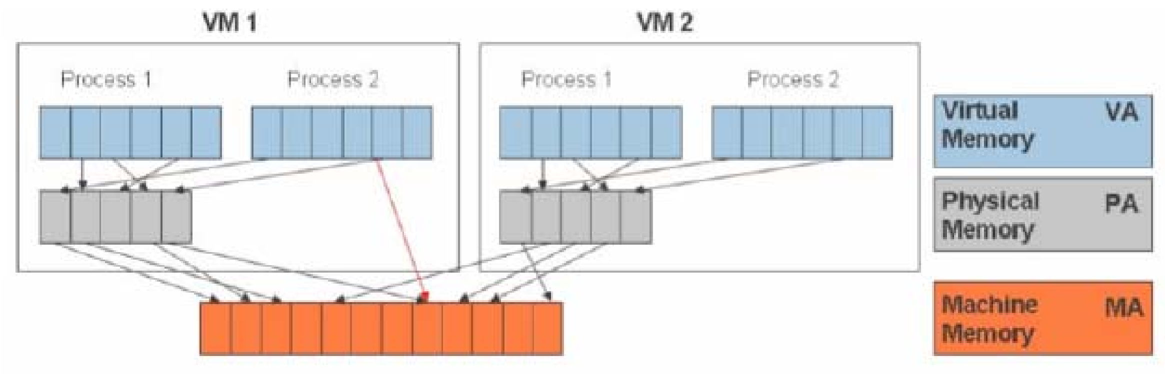
- Properties of Classical Virtualization
  1. Equivalence = **Fidelity**
     - **Program running under a VMM should exhibit a behavior identical to that of running on the equivalent machine**
  2. Efficiency = **Performance**
     - **A statistically dominant fraction of machine instructions may be executed without VMM intervention**
  3. Resource Control = **Safety**
     - **VMM is in full control of virtualized resources**

Strategies: CPU Virtualization



- De-privileging
  - VMM emulates the effect on system/hardware resources of privileged instructions whose execution traps into the VMM
  - aka trap-and-emulate
  - Typically achieved by running GuestOS at a lower hardware priority level than the VMM
  - Problematic on some architectures where privileged instructions do not trap when executed at deprivileged priority

Strategies: Memory Virtualization



Memory Virtualization

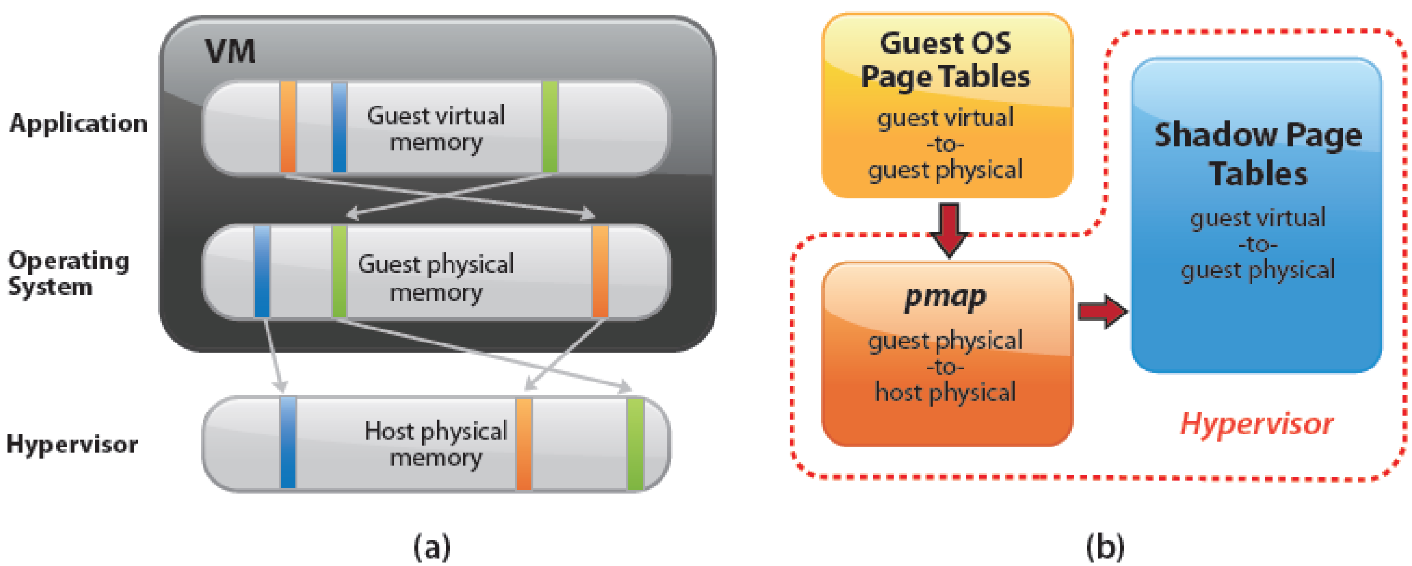
Primary/Shadow structures

- Isolation/protection of Guest OS address spaces
- Avoid the two levels of translation on every access

Memory traces

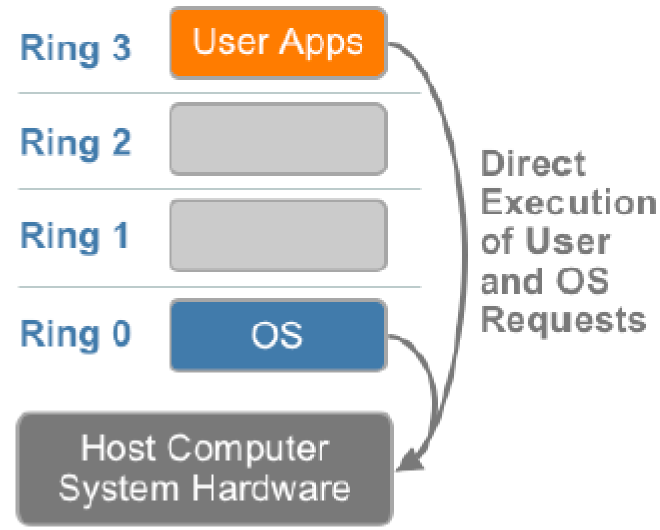
- Efficient MM address translation

Virtual memory levels (a) and memory address translation (b) in ESX



Popek & Goldberg: Classically Virtualizable

- According to Popek and Goldberg,
  - *"an architecture is virtualizable if the set of **sensitive** instructions is a subset of the set of **privileged** instructions."*



x86 privilege level architecture without virtualization

- Is x86 Virtualizable?
  - No

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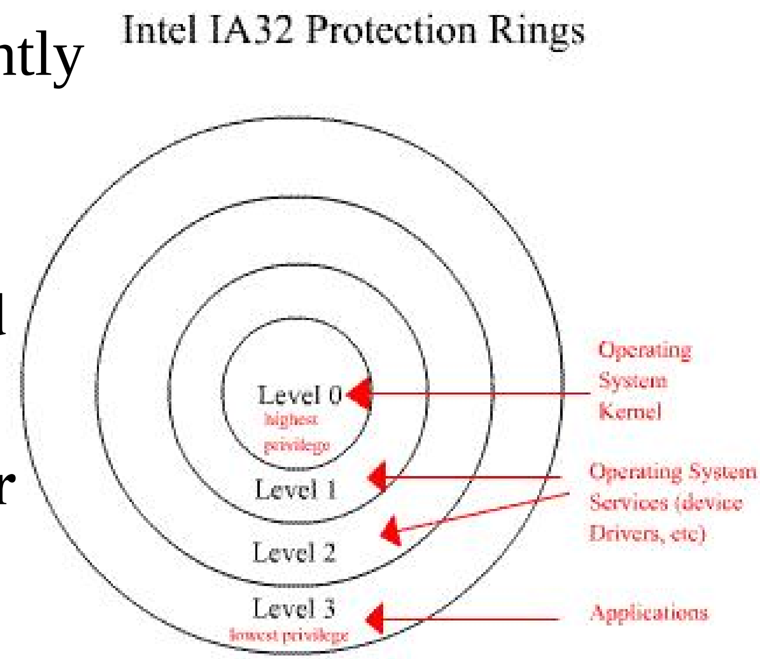
Challenges to x86 Virtualization (1)

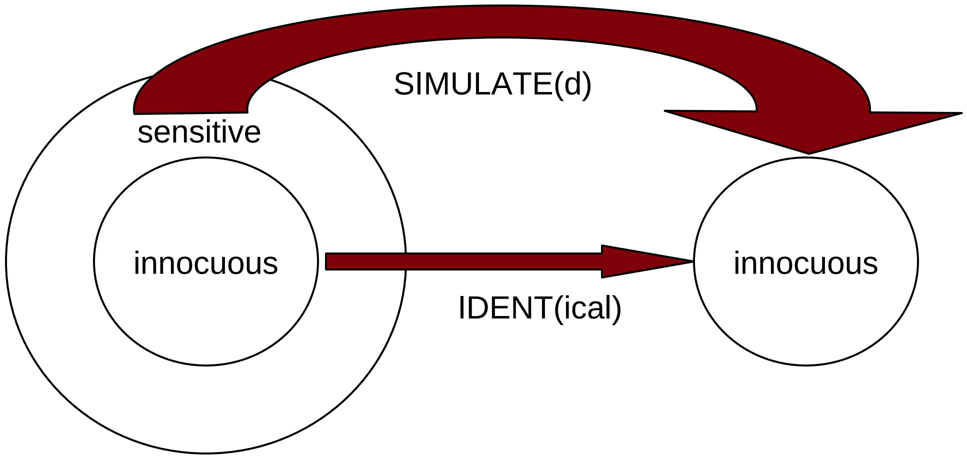
- Lack of trap when privileged instructions run at user-level
  - Classic Example: *popf* instruction
    - Same instruction behaves differently depending on execution mode
    - User Mode: changes ALU flags
    - Kernel Mode: changes ALU **and** system flags
    - **Does not generate a trap in user mode**



Challenges to x86 Virtualization (2)

- Visibility of privileged state
  - Sensitive register instructions: read or change sensitive registers and/or memory locations such as a clock register or interrupt registers:
  - Protection system instructions: reference the storage protection system, memory or address relocation system:

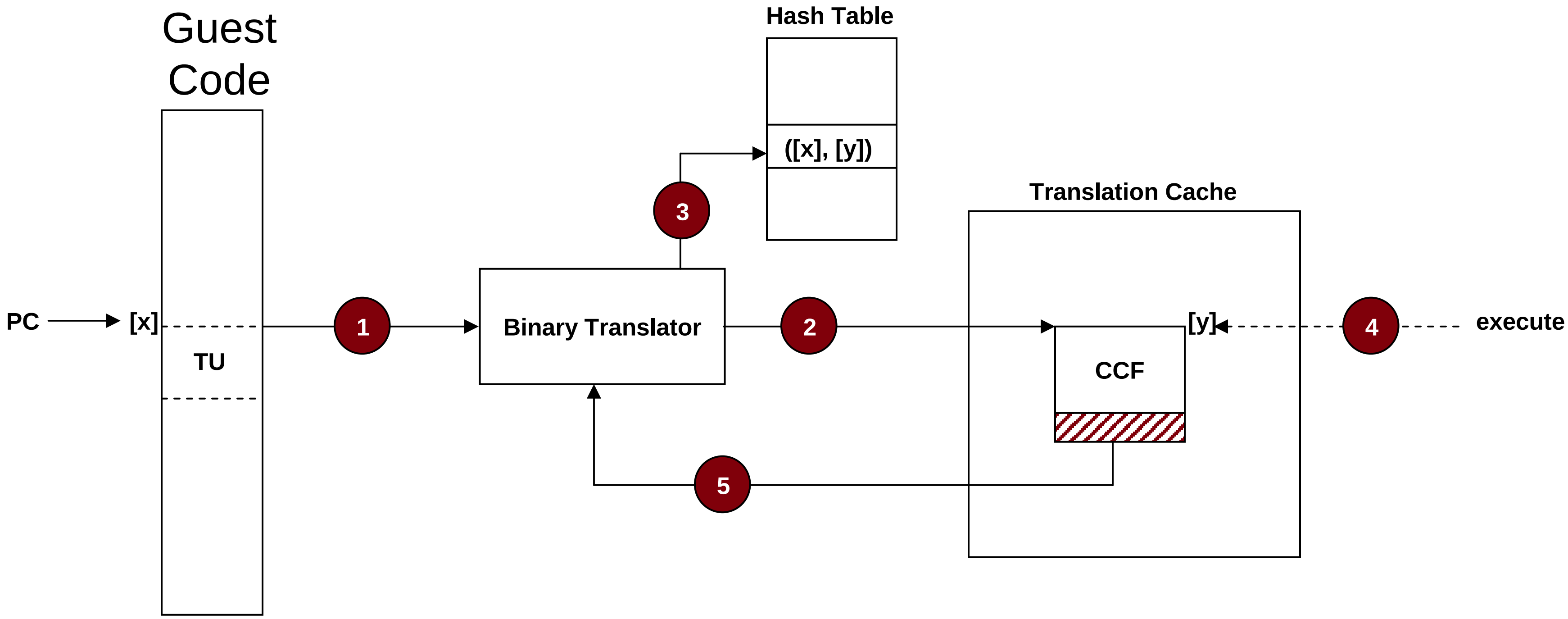
Binary Translation



Characteristics

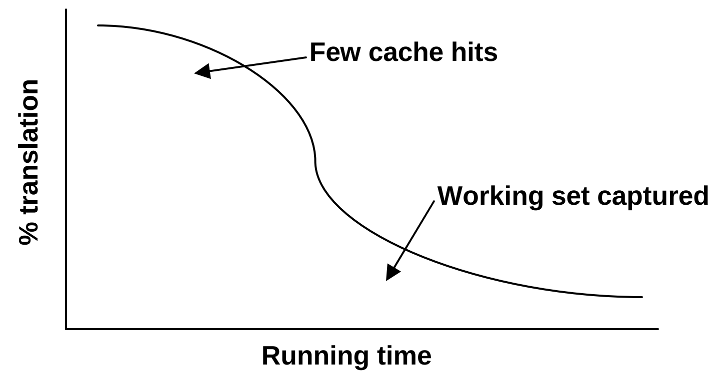
- **Binary** – input is machine-level code
- **Dynamic** – occurs at runtime
- **On demand** – code translated when needed for execution
- **System level** – makes no assumption about guest code
- **Subsetting** – translates from full instruction set to safe subset
- **Adaptive** – adjust code based on guest behavior to achieve efficiency

Binary Translation



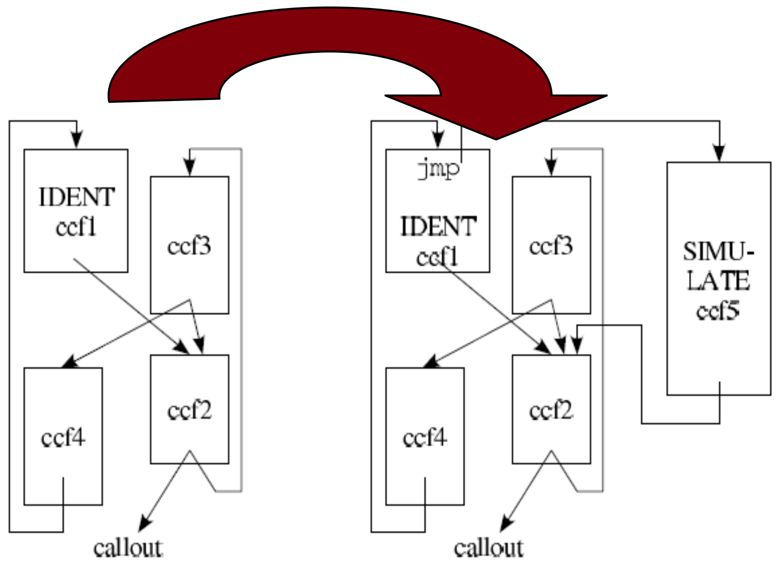
TC: translation cache
TU: translation unit (usually a basic block)
CCF: compiled code fragment

: continuation



Eliminating faults/traps

- Process
  - Privileged instructions – eliminated by simple binary translation (BT)
  - Non-privileged instructions – eliminated by adaptive BT
    - (a) detect a CCF containing an instruction that trap frequently
    - (b) generate a new translation of the CCF to avoid the trap (perhaps inserting a call-out to an interpreter), and patch the original translation to execute the new translation



Binary Translation - Performance Advantages

- Avoid privilege instruction traps
  - Pentium privileged instruction (rdtsc) Trap-and-emulate: 2030 cycles
    - Callout-and-emulate: 1254 cycles
    - BT emulation: 216 cycles (but TSC value is stale)

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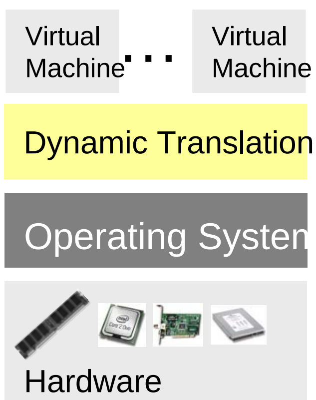
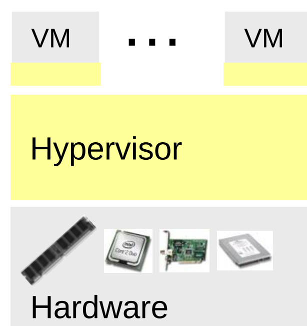
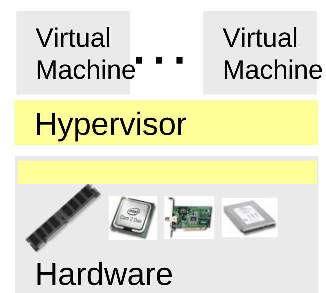
Approaches to Server Virtualization

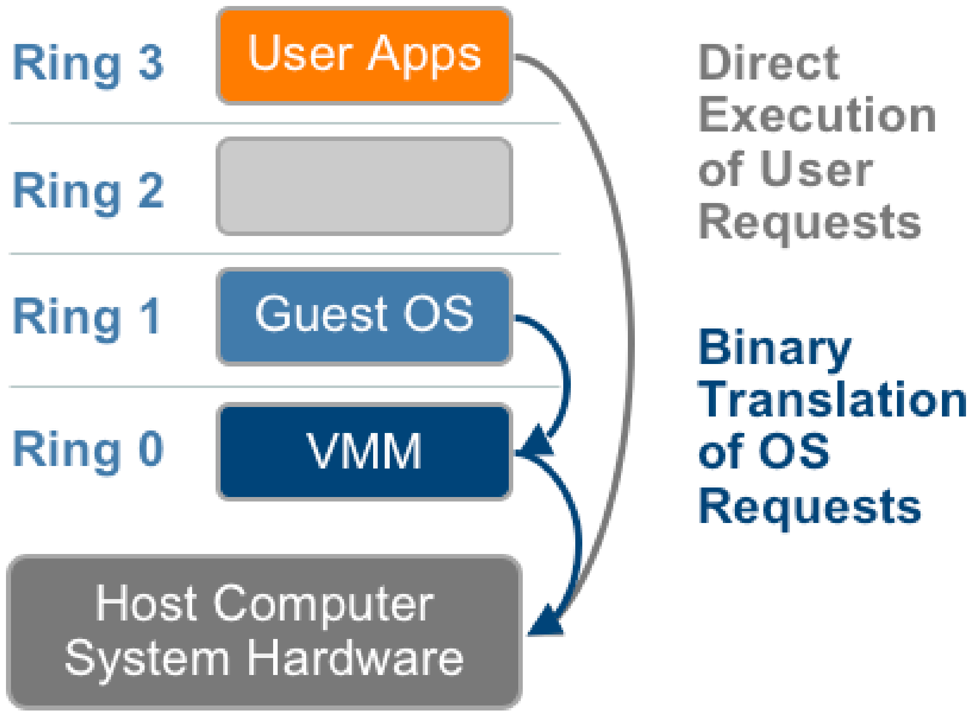
- 1st Generation: Full virtualization (Binary translation)
  - Software Based
  - VMware and Microsoft
- 2nd Generation: Paravirtualization
  - Cooperative virtualization
  - Modified guest
  - VMware, Xen
- 3rd Generation: Silicon-based (Hardware-assisted) virtualization
  - Unmodified guest
  - VMware and Xen on virtualization-aware hardware platforms





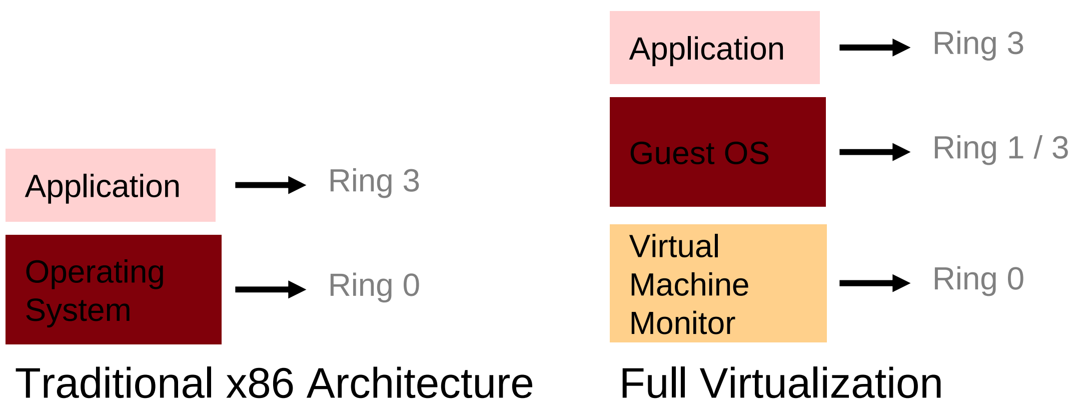


1st Generation: Full Virtualization

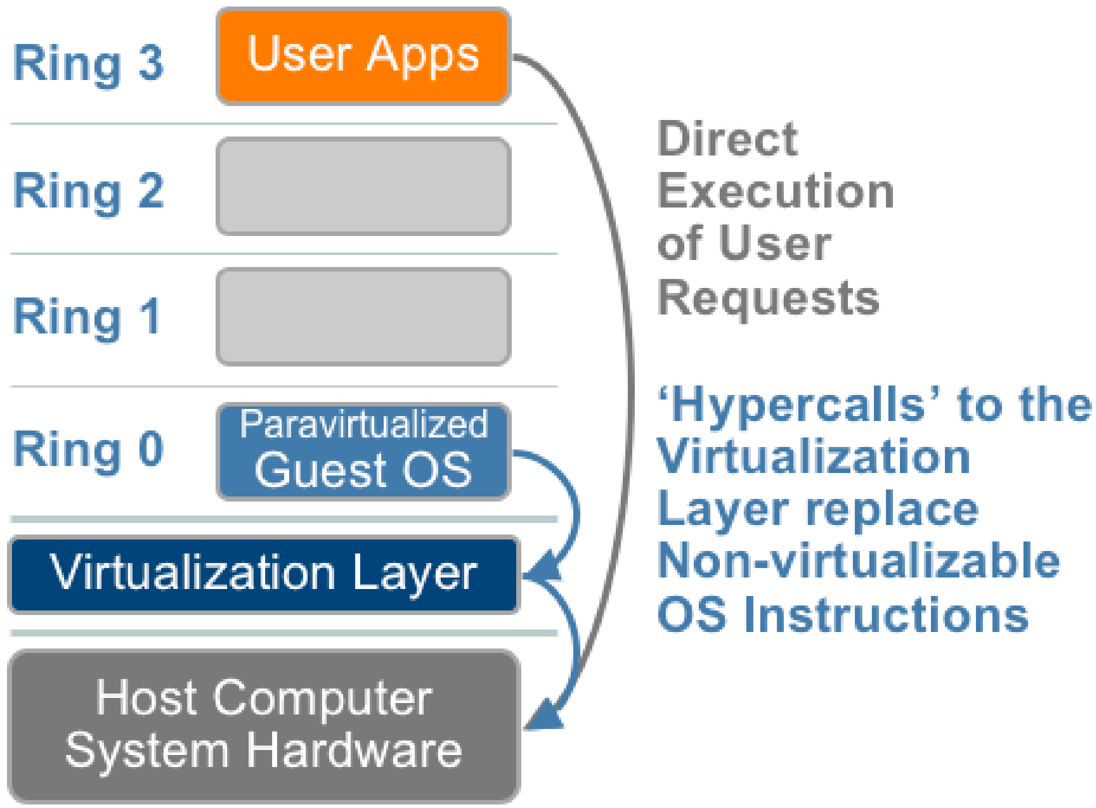


Full Virtualization - Drawbacks

- Hardware emulation comes with a performance price
- In traditional x86 architectures, OS kernels expect to run privileged code in Ring 0
  - However, because Ring 0 is controlled by the host OS, VMs are forced to execute at Ring 1/3, which requires the VMM to trap and emulate instructions
- Due to these performance limitations, paravirtualization and hardware-assisted virtualization were developed



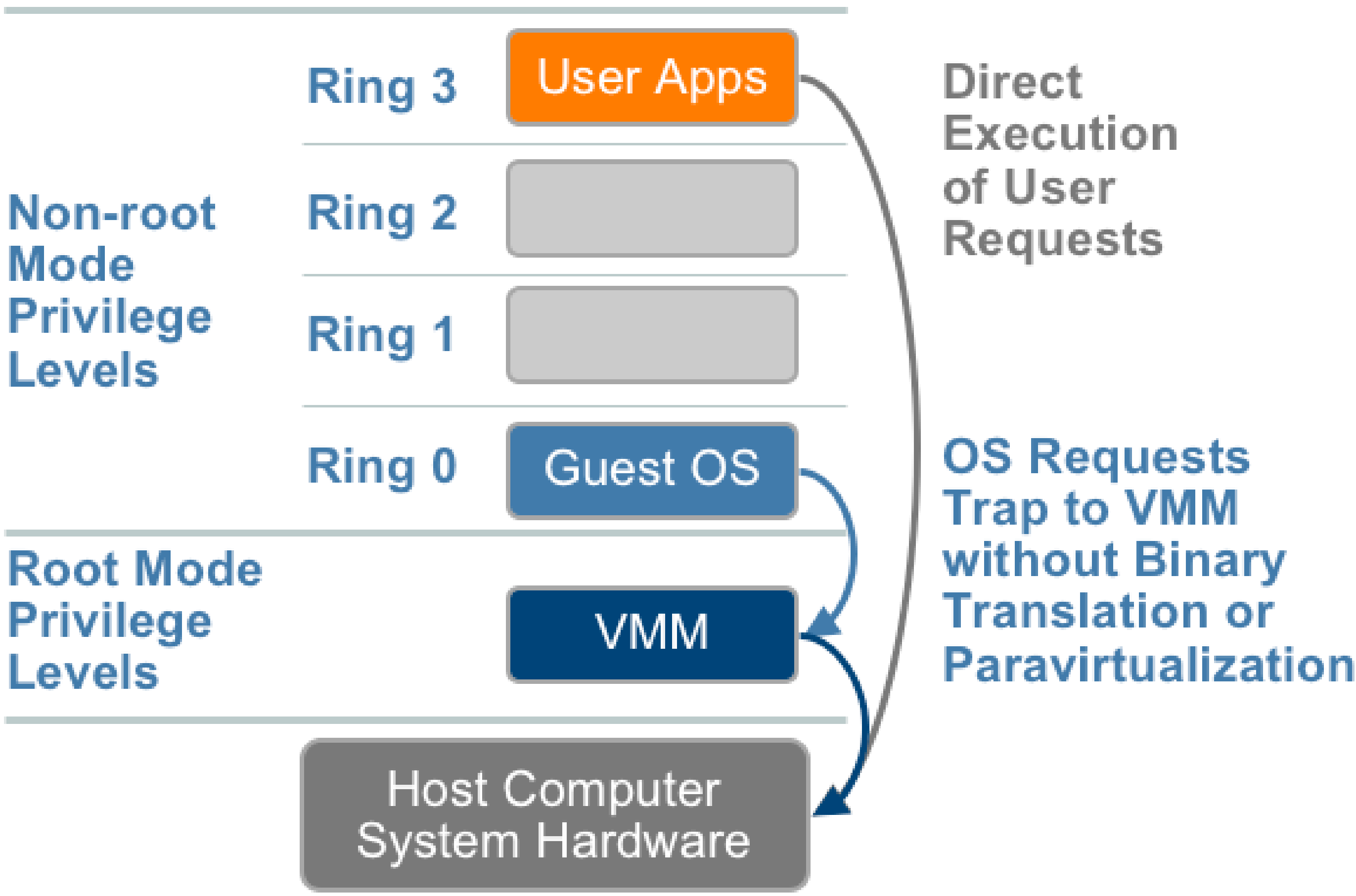
2nd Generation: Paravirtualization



Paravirtualization Challenges

- Guest OS and hypervisor tightly coupled
  - Relies on separate kernel for native and in virtual machine
  - Tight coupling inhibits compatibility
  - Changes to the guest OS are invasive
  - Inhibits maintainability and supportability
  - Guest kernel must be recompiled when hypervisor is updated

Hardware Support for Virtualization



Software vs Hardware

- Hardware extensions allow classical virtualization on the x86.
- The overhead comes with exits – it no exits, then native speed
- Hardware Advantages:
  - Code density is preserved – no translation
  - Precise exceptions – BT performs extra work to recover guest state for faults and interrupts in non-IDENT code
  - System calls run without VMM intervention
- Software Advantages:
  - Trap elimination – replaced with callouts which are usually faster
  - Emulation speed – callouts provide emulation routine whereas hardware must fetch and decode the trapping instruction, then emulate
  - Callout avoidance: BT can avoid a lot of callouts by using in-TC emulation

Summary

	Binary Translation	Hardware Assist	Para-virtualization
Compatibility	**Excellent**	**Excellent**	**Poor**
Performance	**Good**	**Average**	**Excellent**
VMM sophistication	**High**	**Average**	**Average**

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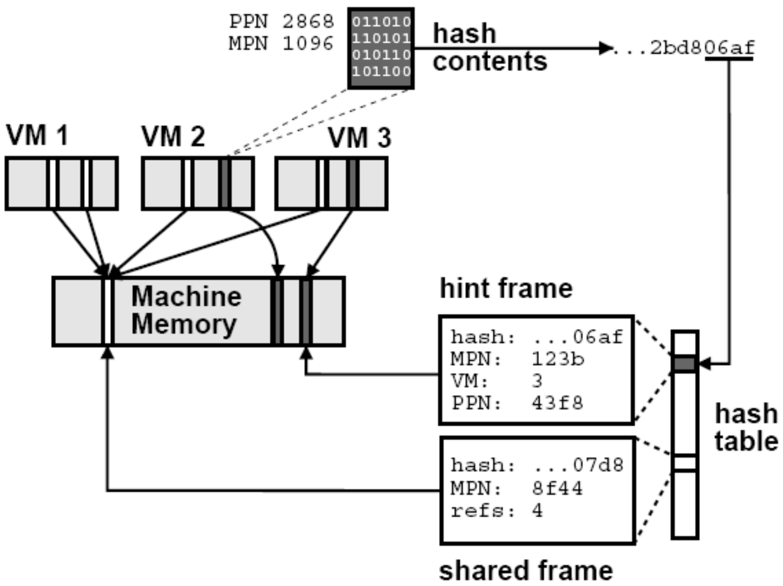
Memory resource management

- VMM (meta-level) memory management
  - Must identify both VM and pages within VM to replace
  - VMM replacement decisions may have unintended interactions with GuestOS page replacement policy
  - Worst-case scenario: double paging

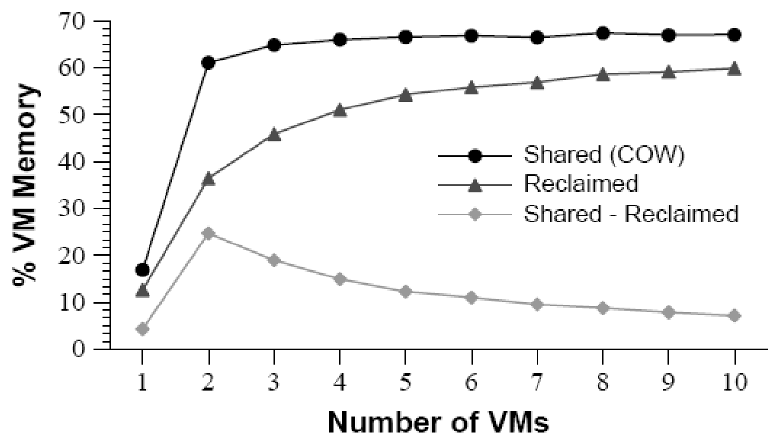
- Strategies
  - Eliminating duplicate pages – even identical pages across different GuestOSs.
    - VMM has sufficient perspective
    - Clear savings when running numerous copies of same GuestOS
  - "ballooning" –
    - add memory demands on GuestOS so that the GuestOS decides which pages to replace
    - Also used in Xen
  - Allocation algorithm
    - Balances memory utilization vs. performance isolation guarantees
    - "taxes" idle memory

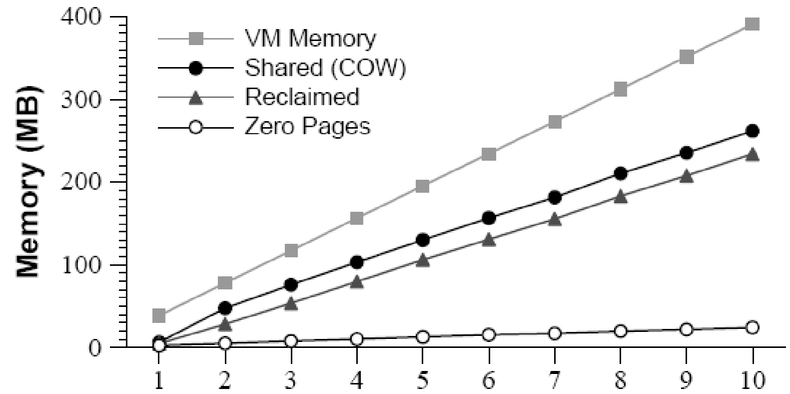
Content-based page sharing

- A hash table contains entries for shared pages already marked "copy-on-write"
- A key for a candidate page is generated from a hash value of the page's contents
- A full comparison is made between the candidate page and a page with a matching key value
- Pages that match are shared – the page table entries for their VMMs point to the same machine page
- If no match is found, a "hint" frame is added to the hash table for possible future matches
- Writing to a shared page causes a page fault which causes a separate copy to be created for the writing GuestOS



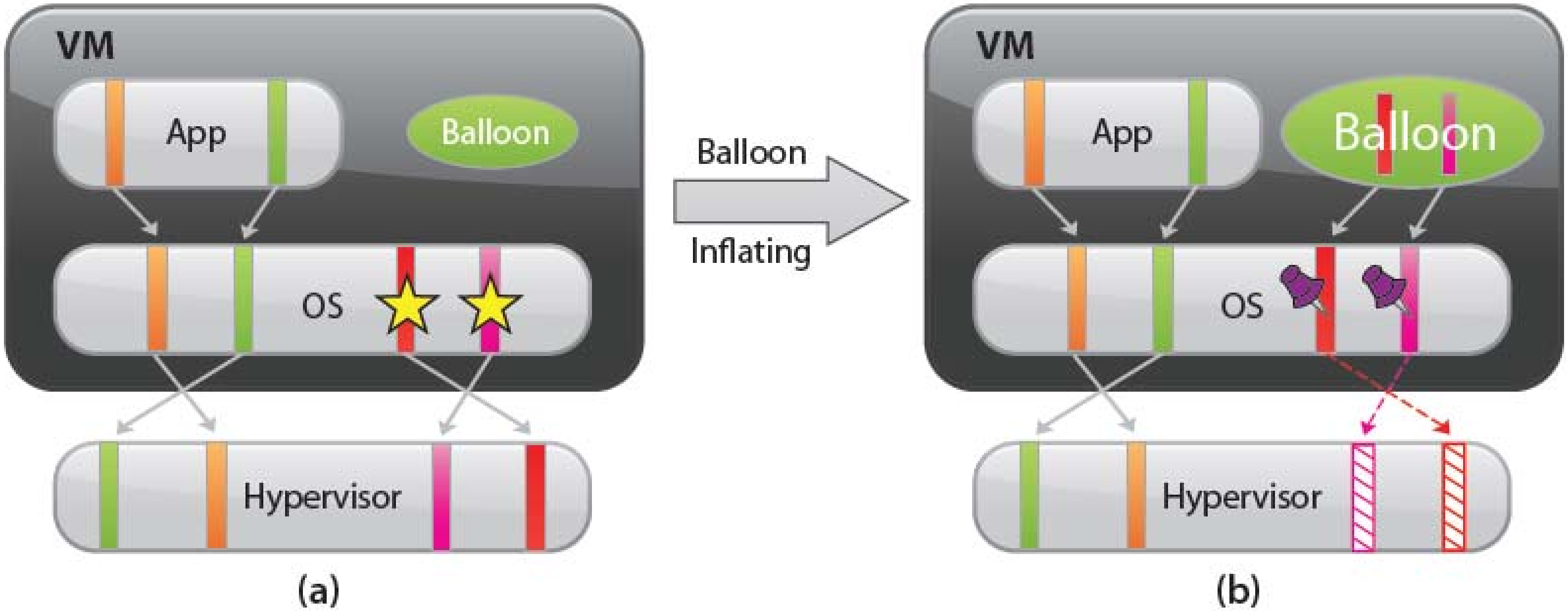
Page sharing performance





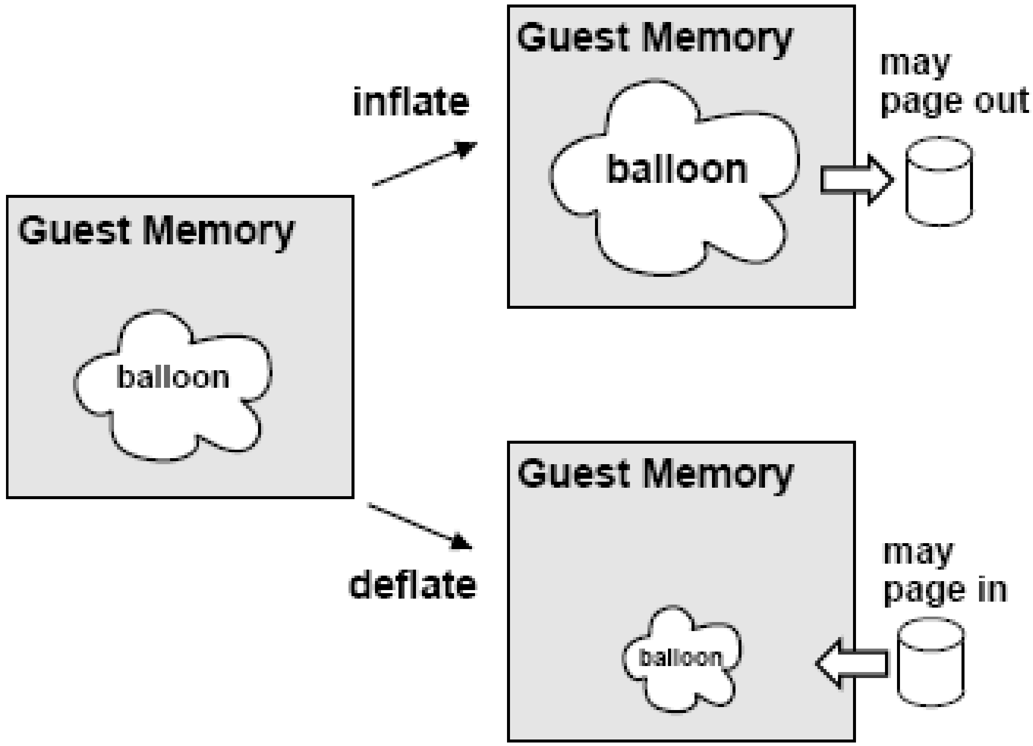
- Identical Linux systems running same benchmark
- “best case” scenario
- Large fraction (67%) of memory sharable
- Considerable amount and percent of memory reclaimed
- Aggregate system throughput essentially unaffected

Ballooning: Inflate



- Inflating the balloon
  - Balloon requests additional “pinned” pages from GuestOS
  - Inflating the balloon causes GuestOS to select pages to be replaced using GuestOS page replacement policy
  - Balloon informs VMM of which physical page frames it has been allocated
  - VMM frees the machine page frames s corresponding to the physical page frames allocated to the balloon (thus freeing machine memory to allocate to other GuestOSs)

Ballooning: Deflate



- Deflating the balloon
  - VMM reclaims machine page frames
  - VMM communicates to balloon
  - Balloon unpins/ frees physical page frames corresponding to new machine page frames
  - GuestOS uses its page replacement policy to page in needed pages

Measuring Cross-VM memory usage

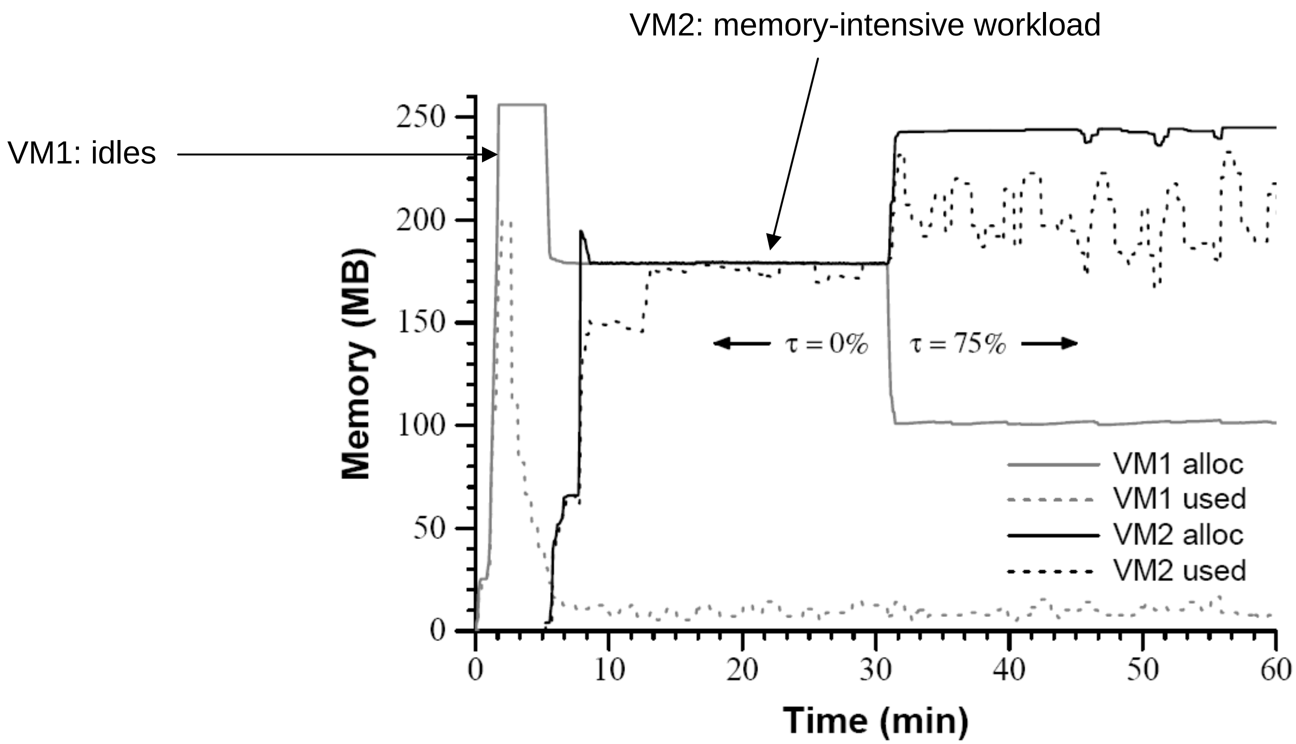
- Each GuestOS is given a number of shares, S, against the total available machine memory.
- The shares-per-page represents the "price" that a GuestOS is willing to pay for a page of memory.
- The price is determined as follows:

$$\rho = \frac{S}{P \cdot (f + k \cdot (1 - f))}$$

shares
price
page allocation
idle page cost
fractional usage

- The idle page cost is $k = 1/(1-\tau)$ where $0 \leq \tau < 1$ is the "tax rate" that defaults to 0.75
- The fractional usage, f, is determined by sampling (what fraction of 100 randomly selected pages are accesses in each 30 second period) and smoothing (using three different weights)

Memory tax experiment



- Initially, VM1 and VM2 converge to same memory allocation with τ=0 (no idle memory tax) despite greater need for memory by VM2
- When idle memory tax applied at default level (75%), VM1 relinquishes memory to VM2 which improves performance of VM2 by over 30%

???

References and Sources

- **A Comparison of Software and Hardware Techniques for x86 Virtualization** *Keith Adams & Ole Agesen*
- **A Comparison of Software and Hardware Techniques for x86 Virtualization** ***Mike Marty***
- **A Comparison of Software and Hardware Techniques for x86 Virtualization** ***Jordan and Justin Ehrlich***
- **A Survey on Virtualization Technologies** ***Susanta K Nanda***
- **Disco: Running Commodity Operating Systems on Scalable Multiprocessors** ***Divya Parekh***
- **Hardware Support for Efficient Virtualization** ***John Fisher-Ogden***
- **Memory Resource Management in VMware ESX Server** ***Carl A. Waldspurger***
- **Memory Resource Management in VMware ESX Server** ***VMware***
- **Resource Management** **Carl A. Waldspurger**
- **Understanding Intel® Virtualization Technology (VT)** ***Dr. Michael L. Collard***

References and Sources

- Understanding *Memory Resource Management* in VMwareo *ESX™ Server* ***VMware***
- Understanding Full Virtualization, Paravirtualization and Hardware Assist ***VMware***
- Virtualization ***Intel and Argentina Software Pathfinding and Innovation***
- VMware and CPU Virtualization Technology ***Jack Lo***
- VMware Virtualization of Oracle and Java ***Scott Drummonds & Tim Harris***
- Lecture on Vmware Dr. Dennis Kafura
- What is Virtualization ***Scott Devine***