Memory Resource Management in VMware ESX Server

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Overview

- Context
- Memory virtualization
- Reclamation
- Sharing
- Allocation policies
- Conclusions

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Motivation

- Server consolidation
  - Many physical servers underutilized
  - Consolidate multiple workloads per machine
- Virtual machines
  - Illusion of dedicated physical machine
  - Encapsulate workload (OS + apps)
  - IBM VM/370 [Creasy '81], Disco [Bugnion '97], VMware [Sugerman '01]
- Resource management
  - Fairness, performance isolation
  - Efficient utilization

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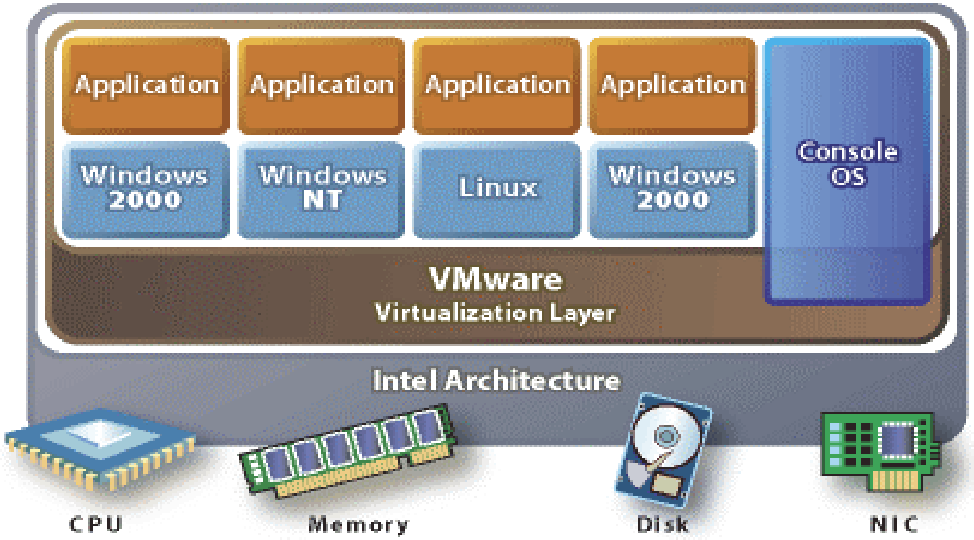
ESX Server



- Commercially-available product
- Thin kernel designed to run VMs
- Multiplex hardware resources
- High-performance I/O

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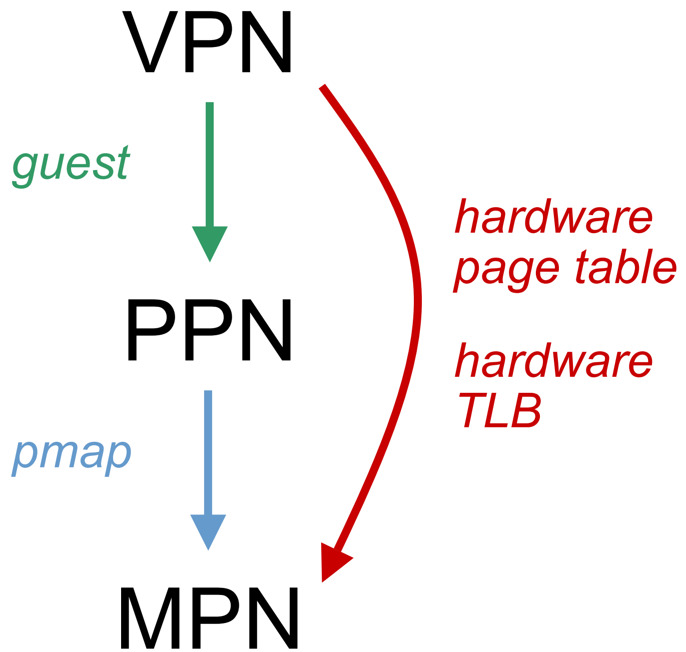
Memory Virtualization

- Traditional VMM approach: extra level of indirection
- virtual → "physical"
  guest maps VPN to PPN
- "physical" → machine
  pmap maps PPN to MPN
- Ordinary memory refs:
  hardware maps VPN to MPN



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Reclaiming Memory

- Traditional: add transparent swap layer
  - Requires meta-level page replacement decisions
  - Best data to guide decisions known only by guest OS
  - Guest and meta-level policies may clash
  - Example: “double paging” anomaly
- Alternative: implicit cooperation
  - Coax guest into doing page replacement
  - Avoid meta-level policy decisions

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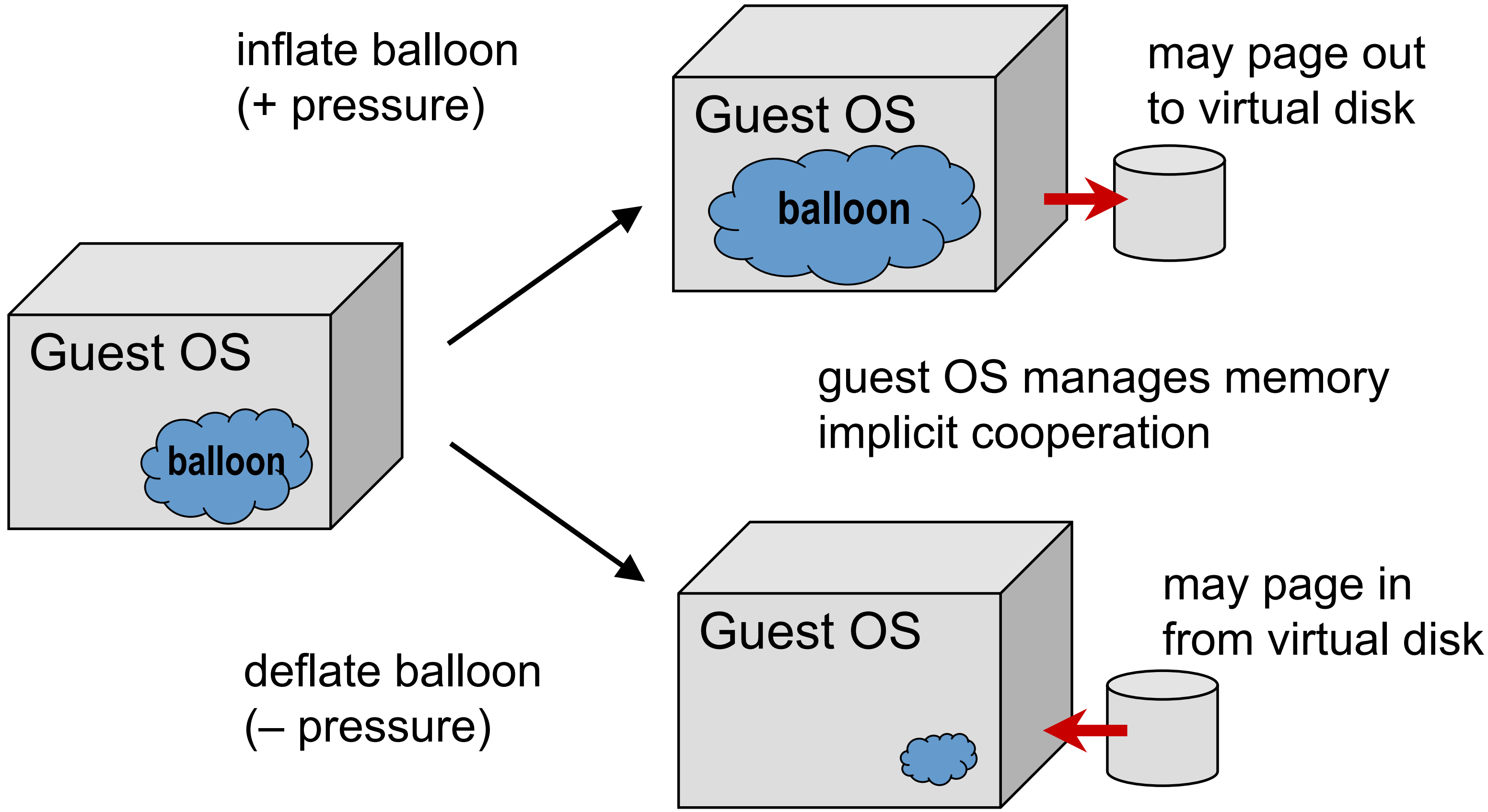
Ballooning



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Ballooning Details

- Guest drivers
  - Inflate: allocate pinned PPNs; backing MPNs reclaimed
  - Use standard Windows/Linux/BSD kernel APIs
  - Related: Nemesis “self-paging” [Hand ’99], Collective [Sapuntzakis ’02]
- Performance benchmark
  - Linux VM, memory-intensive dbench workload
  - Compare 256 MB with balloon sizes 32 – 128 MB vs. static VMs
  - Overhead 1.4% – 4.4%
- Some limitations

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Sharing Memory

- Motivation
  - Multiple VMs running same OS, apps
  - Collapse redundant copies of code, data, zeros
- Transparent page sharing
  - Map multiple PPNs to single MPN copy-on-write
  - Pioneered by Disco [Bugnion ’97], but required guest OS hooks
- New twist: content-based sharing
  - General-purpose, no guest OS changes
  - Background activity saves memory over time

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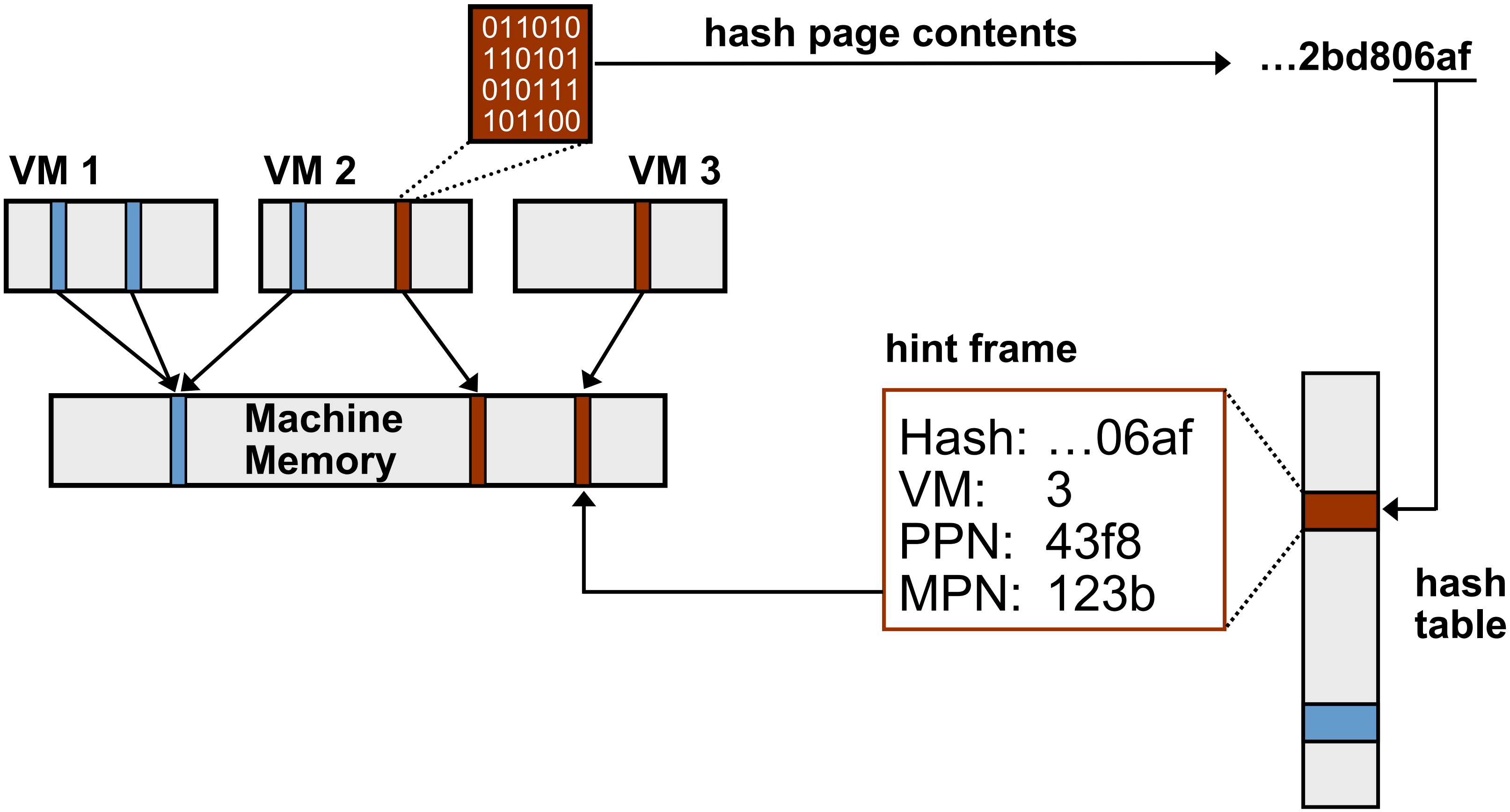
Page Sharing: Scan Candidate PPN



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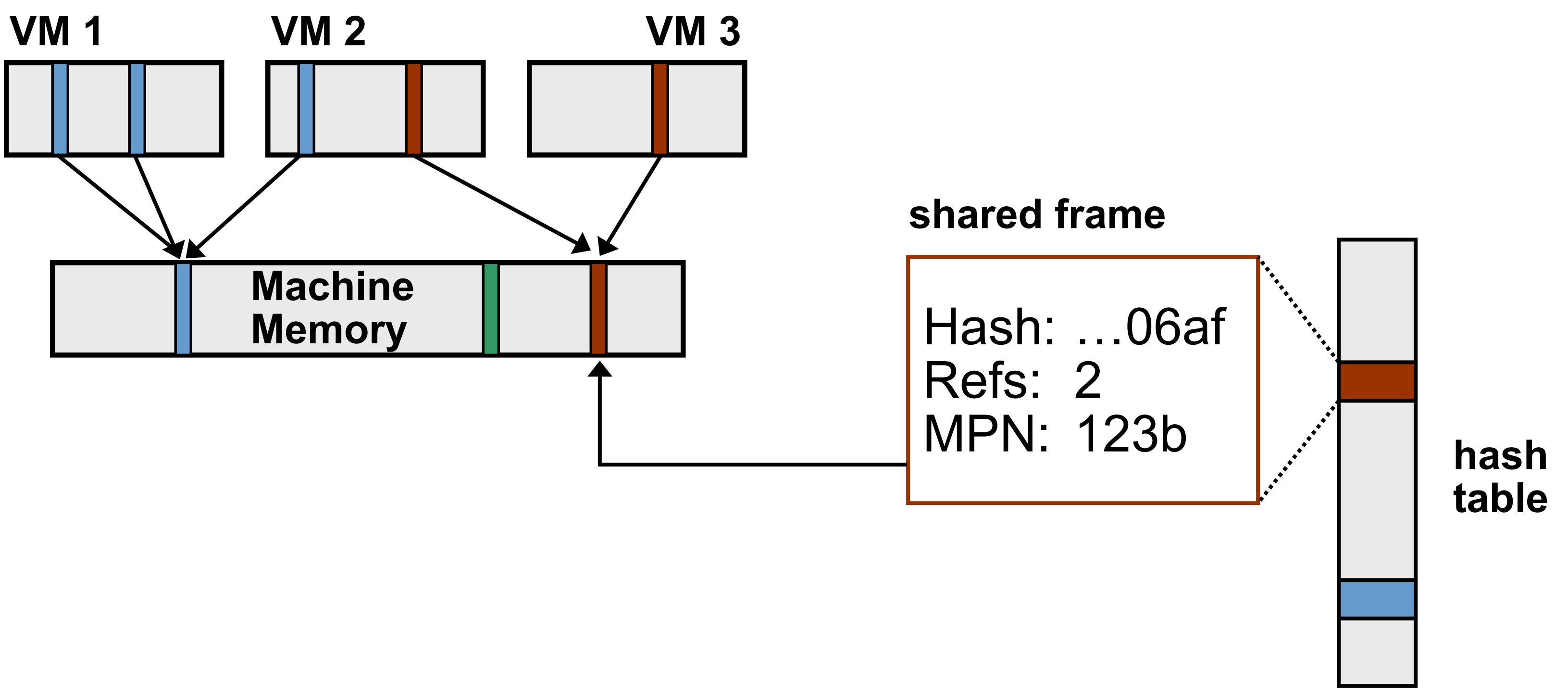
Page Sharing: Successful Match



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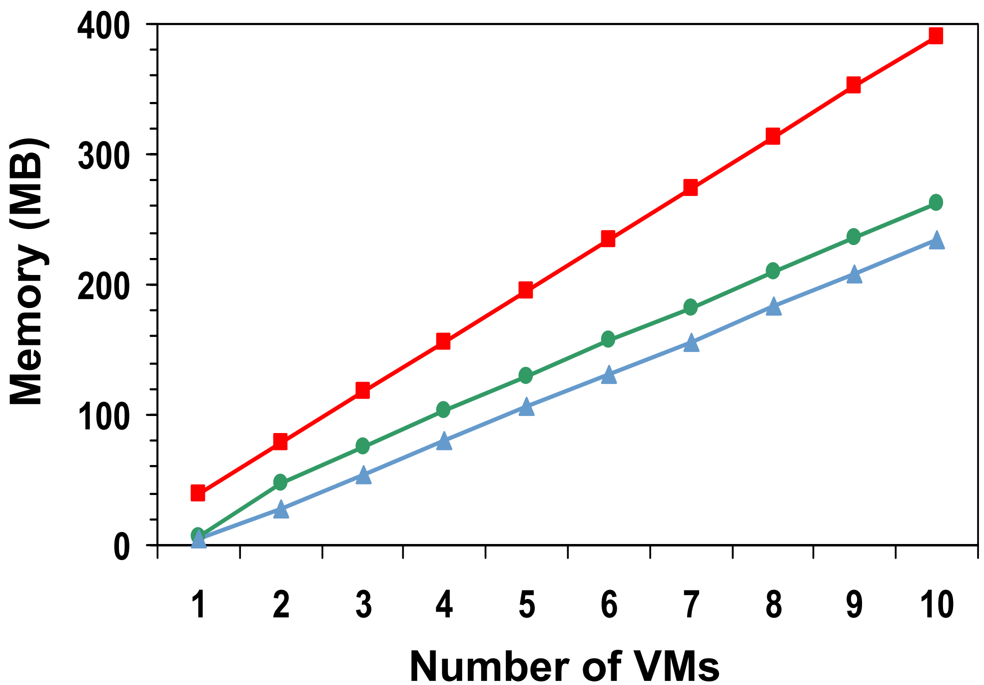
Page Sharing Performance



- "Best-case" workload
  - Identical Linux VMs
  - SPEC95 benchmarks
  - Lots of potential sharing
- Metrics
  - Total guest PPNs
  - Shared PPNs → 67%
  - Saved MPNs → 60%
- Effective sharing
- Negligible overhead

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Real-World Page Sharing

		Total	Saved	
Workload	Guest Types	MB	MB	%
Corporate IT	10 Windows	2048	673	32.9
Nonprofit Org	9 Linux	1846	345	18.7
VMware	5 Linux	1658	120	7.2

Corporate IT – database, web, development servers (Oracle, Websphere, IIS, Java, etc.)

Nonprofit Org – web, mail, anti-virus, other servers (Apache, Majordomo, MailArmor, etc.)

VMware – web proxy, mail, remote access (Squid, Postfix, RAV, ssh, etc.)

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Allocation Parameters

- Min size
  - Guaranteed, even when overcommitted
  - Enforced by admission control
- Max size
  - Amount of “physical” memory seen by guest OS
  - Allocation when undercommitted
- Shares
  - Specify relative importance
  - Proportional-share fairness

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Allocation Policy

- Traditional approach
  - Optimize aggregate system-wide metric
  - Problem: no QoS guarantees, VM importance varies
- Pure share-based approach
  - Revoke from VM with min shares-per-page ratio [Waldspurger ’95]
  - Problem: ignores usage, unproductive hoarding [Sullivan ’00]
- Desired behavior
  - VM gets full share when actively using memory
  - VM may lose pages when working set shrinks

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Reclaiming Idle Memory

- Tax on idle memory
  - Charge more for idle page than active page
  - Idle-adjusted shares-per-page ratio
- Tax rate
  - Explicit administrative parameter
  - 0% ≈ “plutocracy” … 100% ≈ “socialism”
- High default rate
  - Reclaim most idle memory
  - Some buffer against rapid working-set increases

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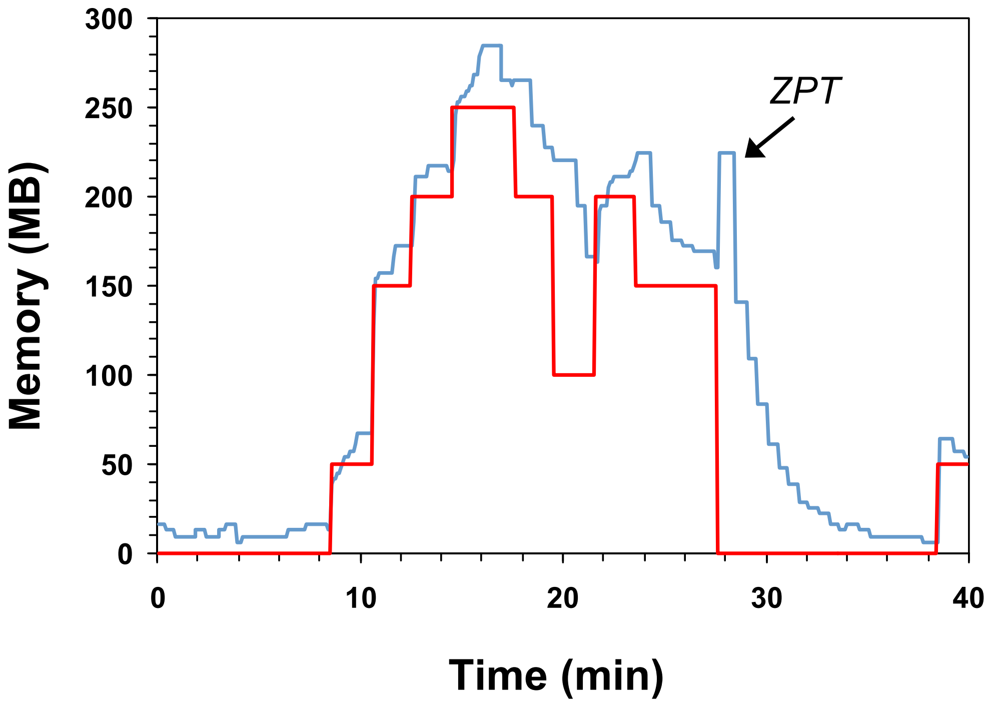
Measuring Active Memory



- Experiment
  - Single Windows VM
  - Memory “toucher” app
  - Active memory estimate
- Statistical sampling
  - Small random subset of pages
  - Software access bits [Joy ’81]
  - Moving averages [Kim ’01]
- Behavior
  - Rapid response to ↑ usage
  - Gradual response to ↓ usage
  - Windows “zero page thread”

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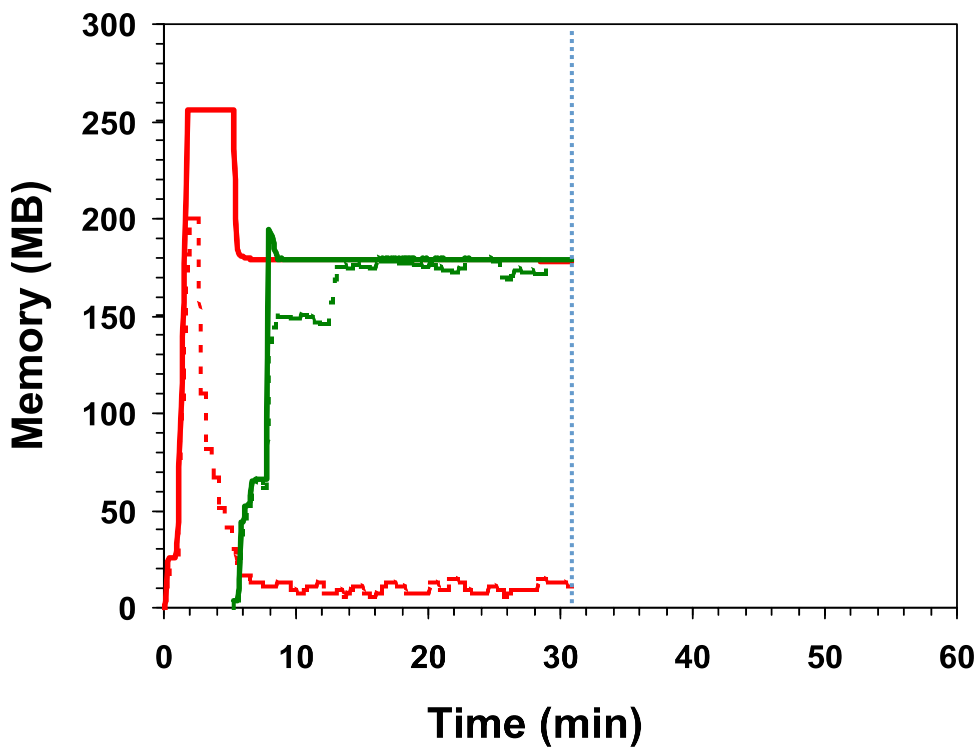
Idle Memory Tax: 0%



- Experiment
  - 2 VMs, 256 MB, same shares
  - VM1: Windows boot+idle
  - VM2: Linux boot+dbench
  - Solid: usage, Dotted: active
- Change tax rate
- Before: no tax
  - VM1 idle, VM2 active
  - get same allocation

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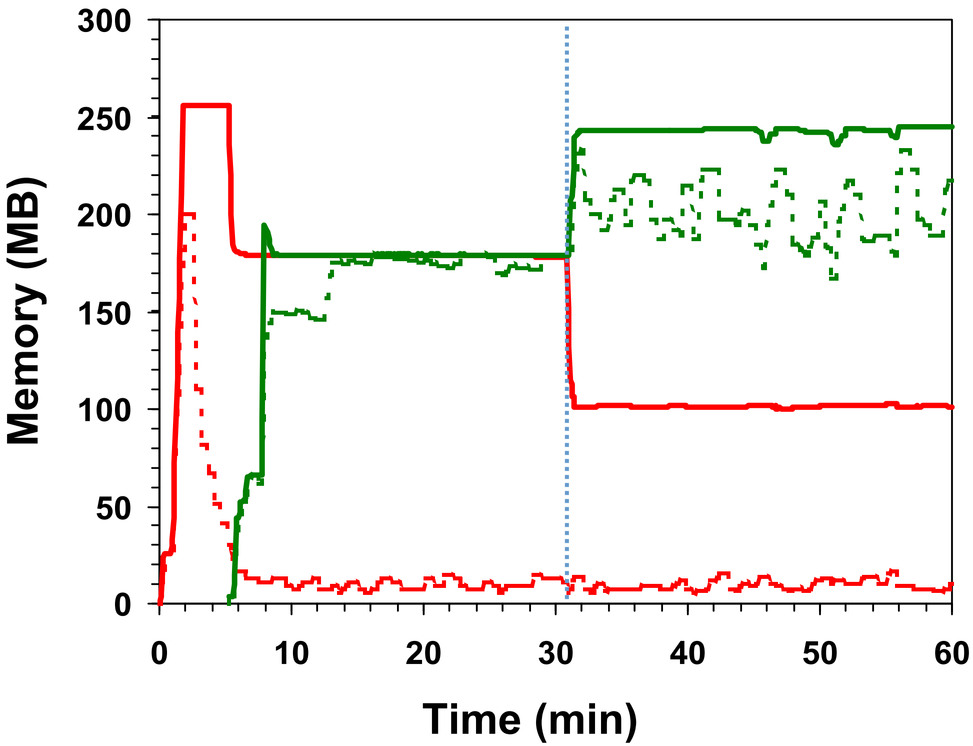
Idle Memory Tax: 75%



- Experiment
  - 2 VMs, 256 MB, same shares
  - VM1: Windows boot+idle
  - VM2: Linux boot+dbench
  - Solid: usage, Dotted: active
- Change tax rate
- After: high tax
  - Redistribute VM1 → VM2
  - VM1 reduced to min size
  - VM2 throughput improves 30%

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Dynamic Reallocation

- Reallocation events
- Enforcing target allocations
  - Ballooning: common-case optimization
  - Swapping: dependable fallback, try sharing first
- Reclamation states
  - High – background sharing
  - Soft – mostly balloon
  - Hard – mostly swap
  - Low – swap and block VMs above target

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Conclusions

- Key features
  - Flexible dynamic partitioning
  - Efficient support for overcommitted workloads
- Novel mechanisms
  - Ballooning leverages guest OS algorithms
  - Content-based page sharing
  - Statistical working-set estimation
- Integrated policies
  - Proportional-sharing with idle memory tax
  - Dynamic reallocation

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Questions?

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Extra Slides

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I/O Page Remapping

- DMA from "high" memory
  - IA-32 PAE mode supports 36-bit addressing (up to 64 GB)
  - Many 32-bit I/O devices (low 4 GB only)
  - VM memory may be located anywhere
- Copy when necessary
  - Conventional approach
  - Use temporary DMA "bounce buffer"
- Dynamic page remapping
  - Keep copy statistics to identify "hot" pages
  - Transparently remap from high to low memory

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