Resource Management for Virtualized Systems

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VMware R&D

Virtualized Resource Management

- Physical resources
  - Actual “host” hardware
  - Processors, memory, I/O devices, etc.
- Virtual resources
  - Virtual “guest” hardware abstractions
  - Processors, memory, I/O devices, etc.
- Resource management
  - Map virtual resources onto physical resources
  - Multiplex physical hardware across VMs
  - Manage contention based on admin policies

Resource Management Goals

- Performance isolation
  - Prevent VMs from monopolizing resources
  - Guarantee predictable service rates
- Efficient utilization
  - Exploit undercommitted resources
  - Overcommit with graceful degradation
- Support flexible policies
  - Meet absolute service-level agreements
  - Control relative importance of VMs

Talk Overview

- Resource controls
- Processor scheduling
- Memory management
- NUMA scheduling
- Distributed systems
- Summary

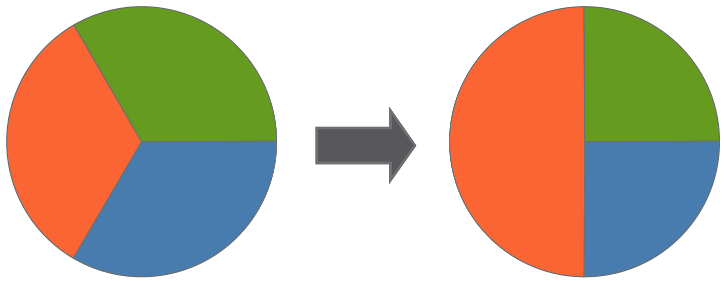
Resource Controls

- Useful features
  - Express absolute service rates
  - Express relative importance
  - Grouping for isolation or sharing
- Challenges
  - Simple enough for novices
  - Powerful enough for experts
  - Physical resource consumption vs. application-level metrics
  - Scaling from single host to cloud

VMware Basic Controls

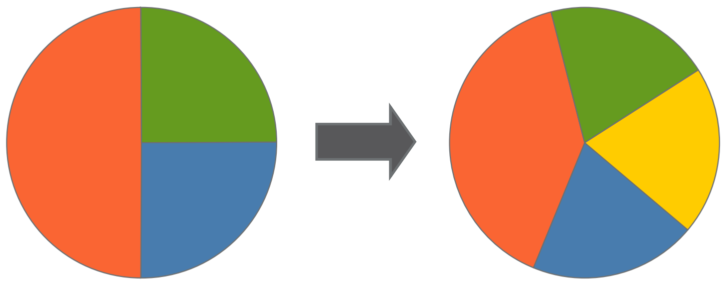
- Shares
  - Specify relative importance
  - Entitlement directly proportional to shares
  - Abstract relative units, only ratios matter
- Reservation
  - Minimum guarantee, even when system overloaded
  - Concrete absolute units (MHz, MB)
  - Admission control: sum of reservations ≤ capacity
- Limit
  - Upper bound on consumption, even if underloaded
  - Concrete absolute units (MHz, MB)

Shares Examples



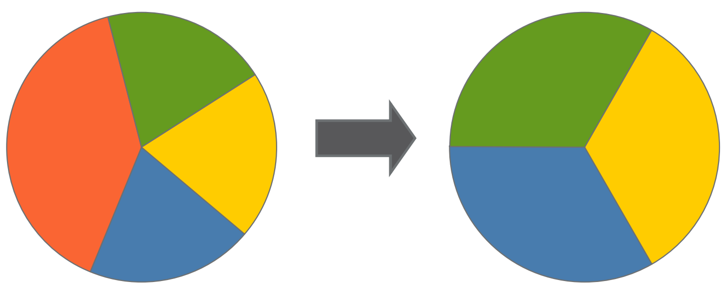
Change shares for **VM**

Dynamic reallocation



Add **VM**, overcommit

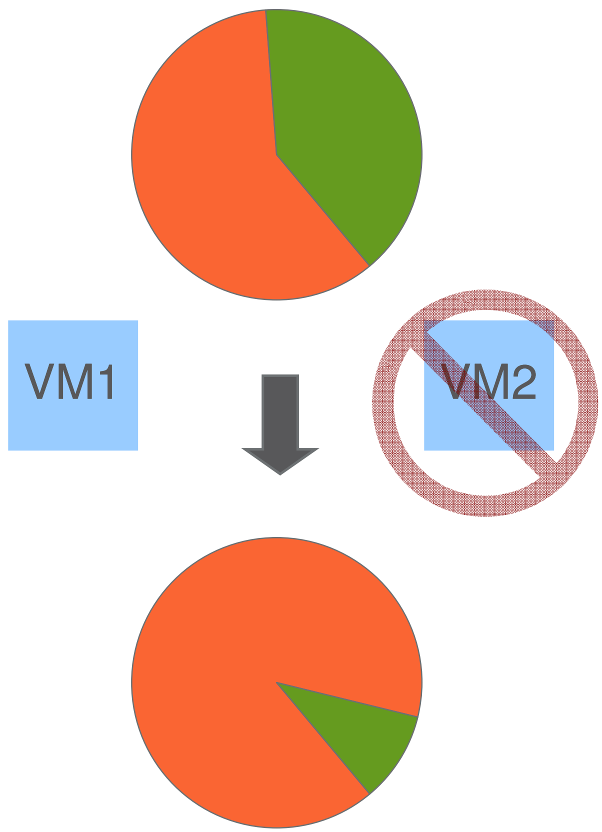
Graceful degradation



Remove **VM**

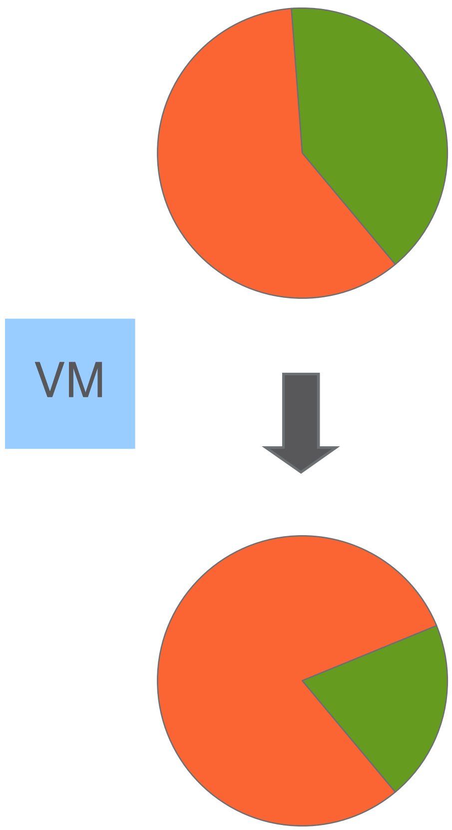
Exploit extra resources

Reservation Example



- Total capacity
  - 1800 MHz reserved
  - 1200 MHz available
- Admission control
  - 2 VMs try to power on
  - Each reserves 900 MHz
  - Unable to admit both
- VM1 powers on
- VM2 not admitted

Limit Example

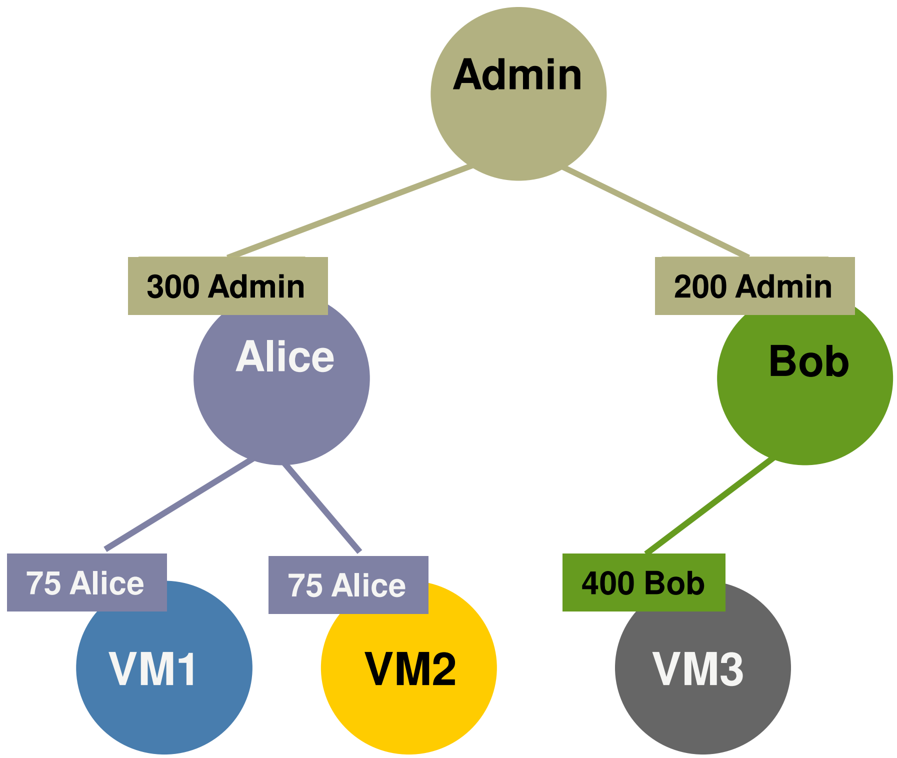


- Current utilization
  - 1800 MHz active
  - 1200 MHz idle
- Start CPU-bound VM
  - 600 MHz limit
  - Execution throttled
- New utilization
  - 2400 MHz active
  - 600 MHz idle
  - VM prevented from using idle resources

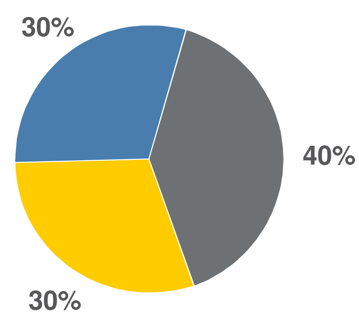
VMware Resource Pools

- Motivation
  - Allocate aggregate resources for sets of VMs
  - Isolation between pools, sharing within pools
  - Flexible hierarchical organization
  - Access control and delegation
- What is a resource pool?
  - Named object with permissions
  - Reservation, limit, and shares for each resource
  - Parent pool, child pools, VMs

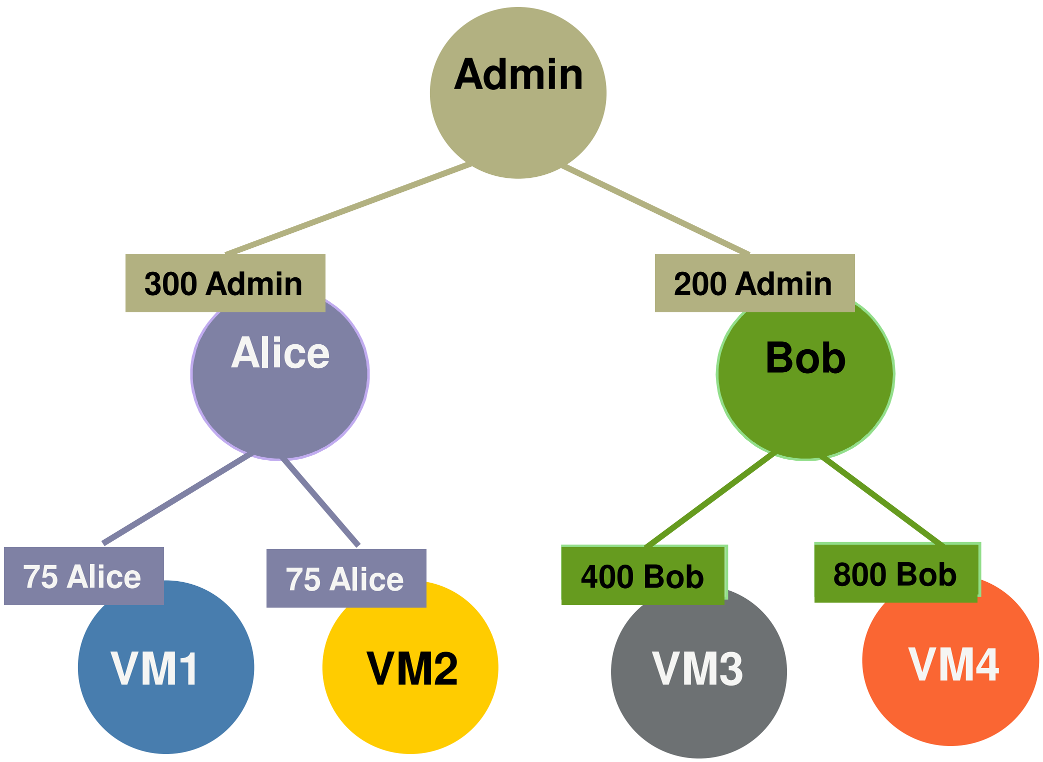
Resource Pools Example



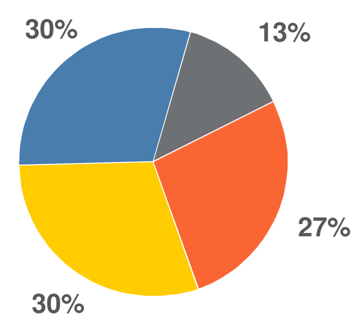
- Admin manages users
- Policy: Alice's share is 50% more than Bob's
- Users manage own VMs
- Not shown: resvs, limits
- VM allocations:



Example: Bob Adds VM



- Same policy
- Pools isolate users
- Alice still gets 50% more than Bob
- VM allocations:



Resource Controls: Future Directions

- Application-level metrics
  - Users think in terms of transaction rates, response times
  - Requires detailed app-specific knowledge and monitoring
  - Can layer on top of basic physical resource controls
- Other controls?
  - Real-time latency guarantees
  - Price-based mechanisms and multi-resource tradeoffs
- Emerging DMTF standard
  - Reservation, limit, “weight” + resource pools
  - Authors from VMware, Microsoft, IBM, Citrix, etc.

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Processor Scheduling

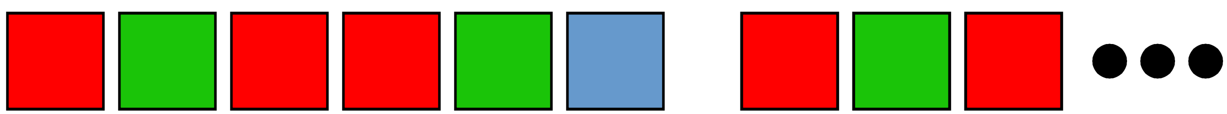
- Useful features
  - Accurate rate-based control
  - Support both UP and SMP VMs
  - Exploit multi-core, multi-threaded CPUs
  - Grouping mechanism
- Challenges
  - Efficient scheduling of SMP VMs
  - VM load balancing, interrupt balancing
  - Cores/threads may share cache, functional units
  - Lack of control over µarchitectural fairness
  - Proper accounting for interrupt-processing time

VMware Processor Scheduling

- Scheduling algorithms
  - Rate-based controls
  - Hierarchical resource pools
  - Inter-processor load balancing
  - Accurate accounting
- Multi-processor VM support
  - Illusion of dedicated multi-processor
  - Near-synchronous co-scheduling of VCPUs
  - Support hot-add VCPUs
- Modern processor support
  - Multi-core sockets with shared caches
  - Simultaneous multi-threading (SMT)

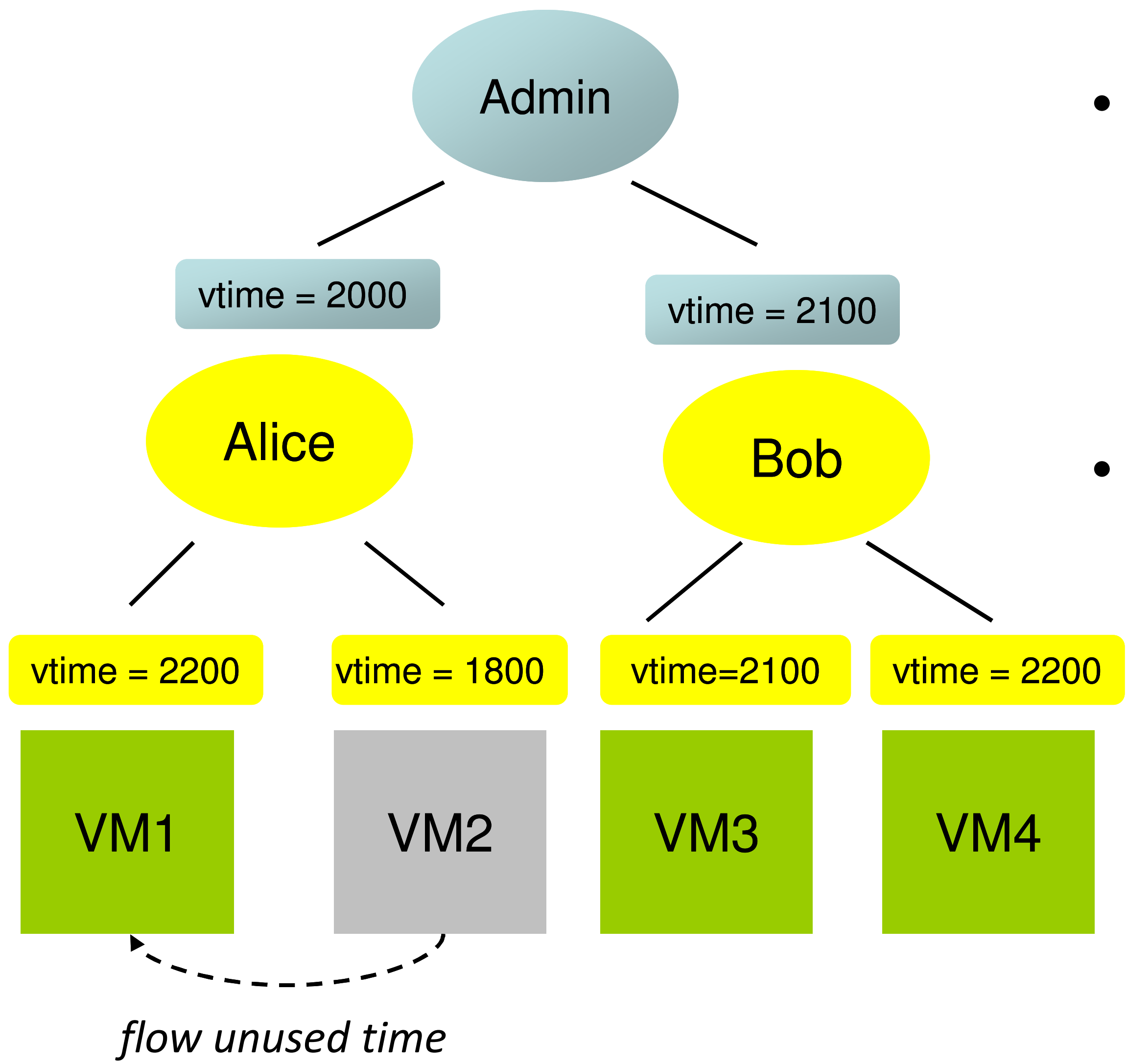
Proportional-Share Scheduling

- Simplified virtual-time algorithm
  - Virtual time = usage / shares
  - Schedule VM with smallest virtual time
- Example: 3 VMs A, B, C with 3 : 2 : 1 share ratio



A	2	4	4	6	8	8	8	10	10
B	3	3	6	6	6	9	9	9	12
C	6	6	6	6	6	6	12	12	12

Hierarchical Scheduling



- Motivation
  - Enforce fairness at each resource pool
  - Unused resources flow to closest relatives
- Approach
  - Maintain virtual time at each node
  - Recursively choose node with smallest virtual time

Inter-Processor Load Balancing

- Motivation
  - Utilize multiple processors efficiently
  - Enforce global fairness
  - Amortize context-switch costs
  - Preserve cache affinity
- Approach
  - Per-processor dispatch and run queues
  - Scan remote queues periodically for fairness
  - Pull whenever a physical CPU becomes idle
  - Push whenever a virtual CPU wakes up
  - Consider cache affinity cost-benefit

Co-Scheduling SMP VMs

- Motivation
  - Maintain illusion of dedicated multiprocessor
  - Correctness: avoid guest BSODs / panics
  - Performance: consider guest OS spin locks
- VMware Approach
  - Limit "skew" between progress of virtual CPUs
  - Idle VCPUs treated as if running
  - Deschedule VCPUs that are too far ahead
  - Schedule VCPUs that are behind
- Alternative: Para-virtualization

Charging and Accounting

- Resource usage accounting
  - Pre-requisite for enforcing scheduling policies
  - Charge VM for consumption
  - Also charge enclosing resource pools
  - Adjust accounting for SMT systems
- System time accounting
  - Time spent handling interrupts, BHs, system threads
  - Don’t penalize VM that happened to be running
  - Instead charge VM on whose behalf work performed
  - Based on statistical sampling to reduce overhead

Processor Scheduling: Future Directions

- Shared cache management
  - Explicit cost-benefit tradeoffs for migrations
    e.g. based on cache miss-rate curves (MRCs)
  - Compensate VMs for co-runner interference
  - Hardware cache QoS techniques
- Power management
  - Exploit frequency and voltage scaling (P-states)
  - Exploit low-power, high-latency halt states (C-states)
  - Without compromising accounting and rate guarantees

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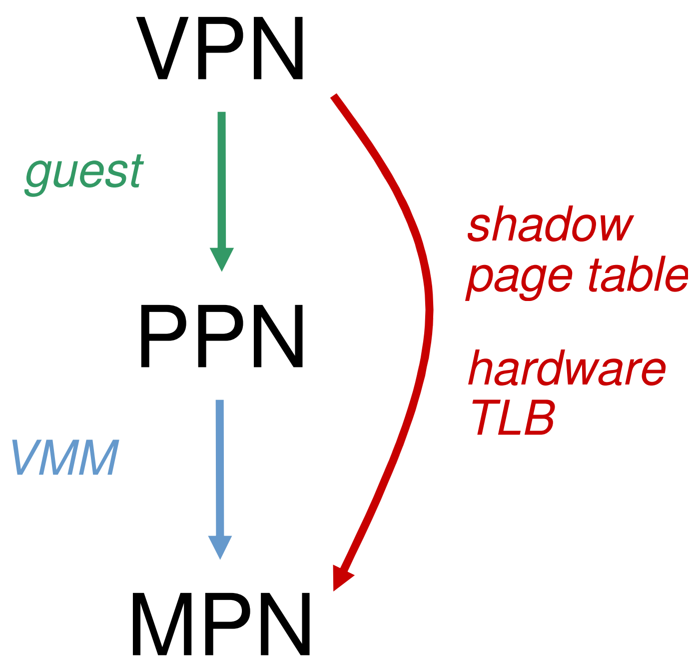
Memory Management

- Useful features
  - Efficient memory overcommitment
  - Accurate resource controls
  - Exploit deduplication opportunities
  - Leverage hardware capabilities
- Challenges
  - Reflecting both VM importance and working-set
  - Best data to guide decisions private to guest OS
  - Guest and meta-level policies may clash

Memory Virtualization

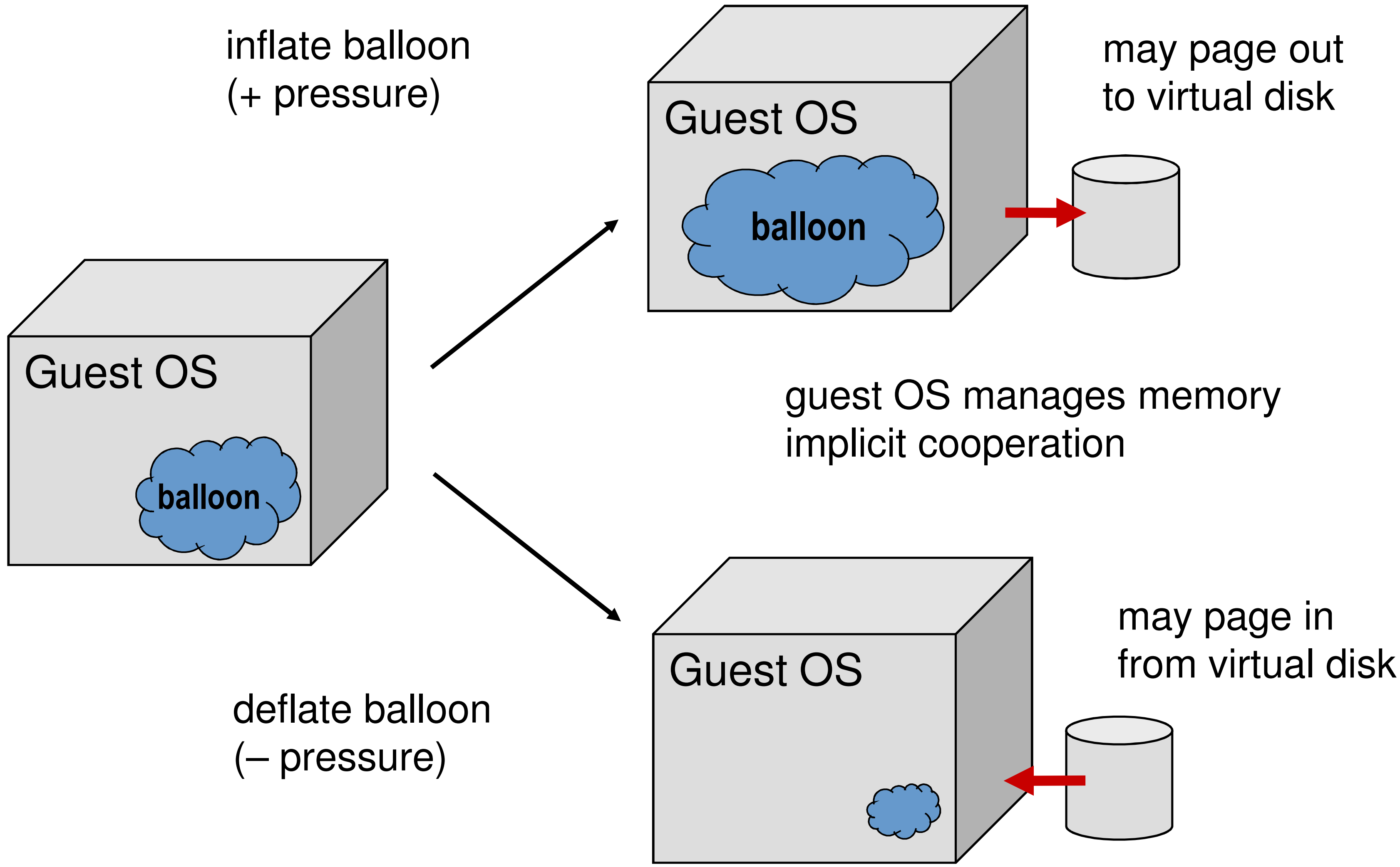


- Extra level of indirection
  - Virtual → "Physical"
    Guest maps VPN to PPN
    using primary page tables
  - "Physical" → Machine
    VMM maps PPN to MPN
- Shadow page table
  - Traditional VMM approach
  - Composite of two mappings
  - For ordinary memory references, hardware maps VPN to MPN
- Nested page table hardware
  - Recent AMD RVI, Intel EPT
  - VMM manages PPN-to-MPN table
  - No need for software shadows

Reclaiming Memory

- Required for memory overcommitment
  - Increase consolidation ratio, incredibly valuable
  - Not supported by most hypervisors
  - Many VMware innovations [Waldspurger OSDI ’02]
- Traditional: add transparent swap layer
  - Requires meta-level page replacement decisions
  - Best data to guide decisions known only by guest
  - 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

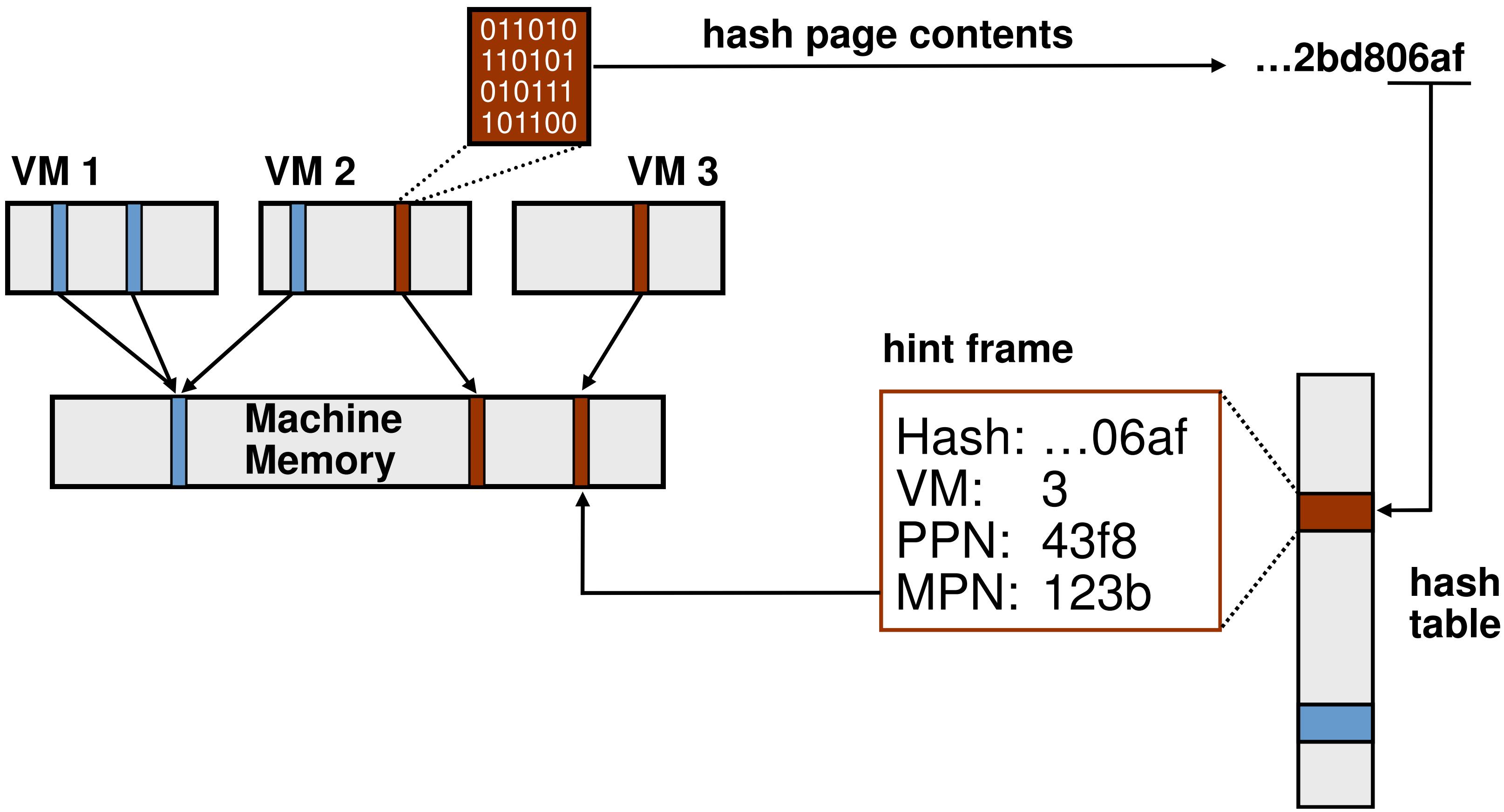
Ballooning


inflate balloon
(+ pressure)
Guest OS
balloon
may page out
to virtual disk
Guest OS
balloon
guest OS manages memory
implicit cooperation
deflate balloon
(– pressure)
Guest OS
may page in
from virtual disk

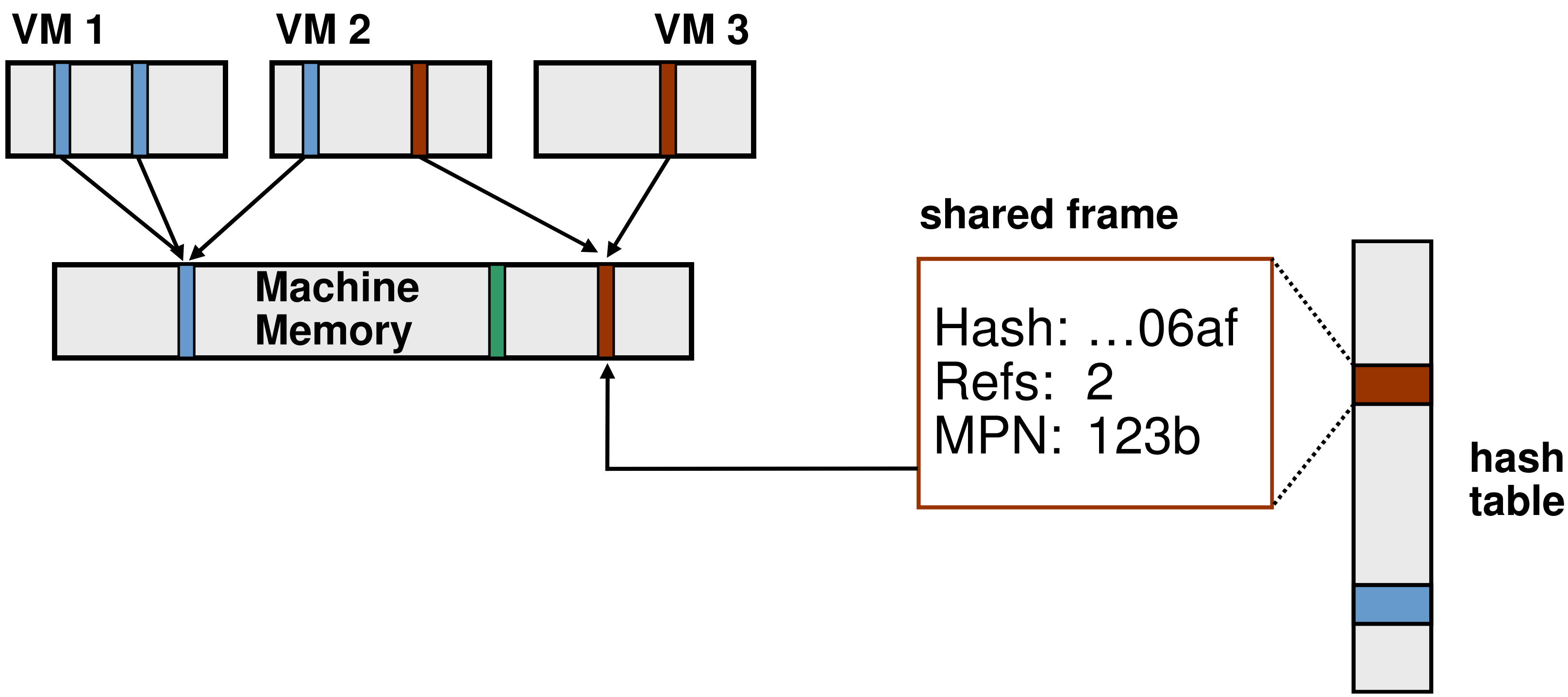
Page Sharing

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

Page Sharing: Scan Candidate PPN



Page Sharing: Successful Match



Memory Reclamation: Future Directions

- Memory compression
  - Old idea: compression cache [Douglis USENIX ’93], Connectix RAMDoubler (MacOS mid-90s)
  - Recent: Difference Engine [Gupta et al. OSDI ’08], future VMware ESX release
- Sub-page deduplication
- Emerging memory technologies
  - Swapping to SSD devices
  - Leveraging phase-change memory

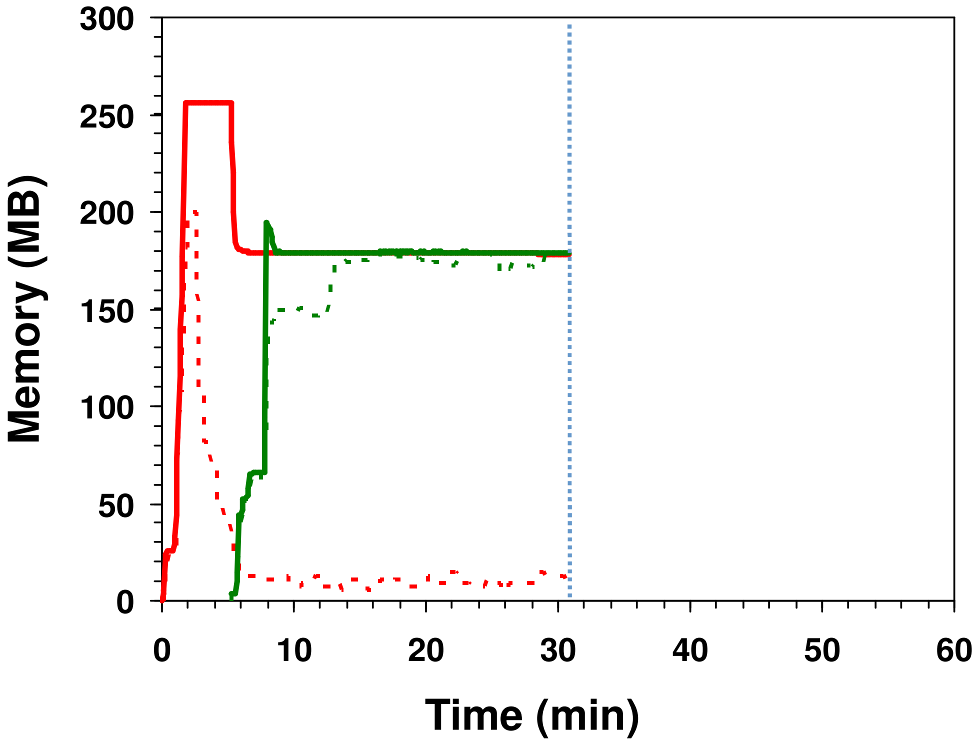
Memory Allocation Policy

- 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
  - Problem: ignores usage, unproductive hoarding
- Desired behavior
  - VM gets full share when actively using memory
  - VM may lose pages when working-set shrinks

Reclaiming Idle Memory

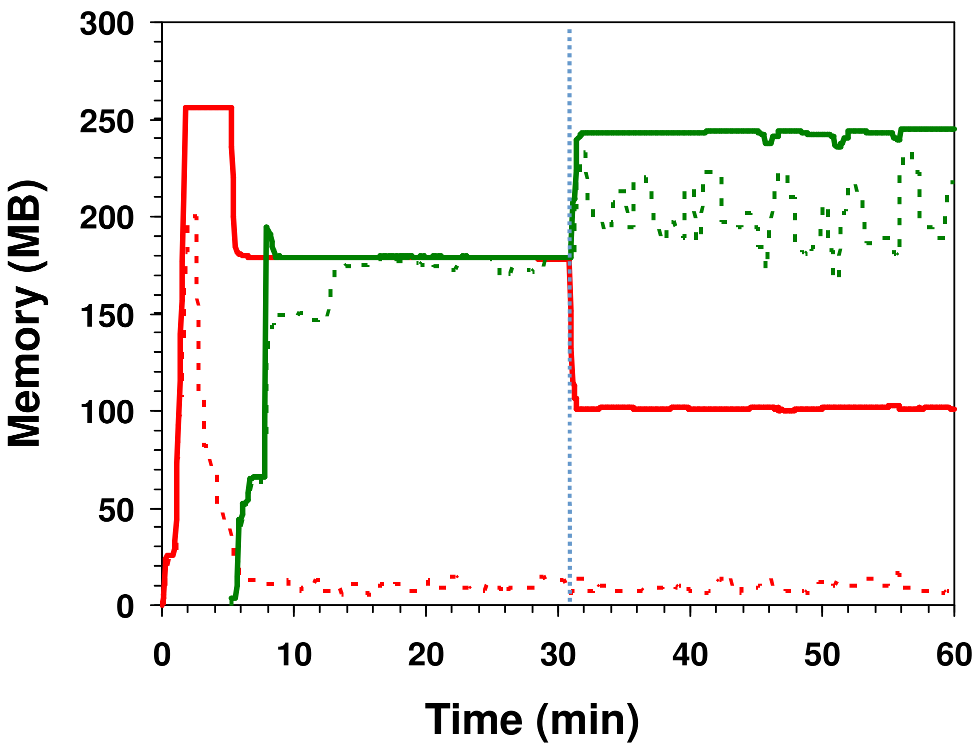
- Tax on idle memory
  - Charge more for idle page than active page
  - Idle-adjusted shares-per-page ratio
- Tax rate
  - Explicit administrative parameter
  - 0% ≈ "plutocracy" … 100% ≈ "socialism"
- High default rate
  - Reclaim most idle memory
  - Some buffer against rapid working-set increases

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

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
  - Redistributed VM1 → VM2
  - VM1 reduces to min size
  - VM2 throughput improves more than 30%

Allocation Policy: Future Directions

- Memory performance estimates
  - Estimate effect of changing allocation
  - Miss-rate curve (MRC) construction
- Improved coordination of mechanisms
  - Ballooning, compression, SSD, swapping
- Leverage guest hot-add/remove
- Large page allocation efficiency and fairness

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NUMA Scheduling

- NUMA platforms
  - Non-uniform memory access
  - Node = processors + local memory + cache
  - Examples: IBM x-Series, AMD Opteron, Intel Nehalem
- Useful features
  - Automatically map VMs to NUMA nodes
  - Dynamic rebalancing
- Challenges
  - Tension between memory locality and load balance
  - Lack of detailed counters on commodity hardware

VMware NUMA Scheduling

- Periodic rebalancing
  - Compute VM entitlements, memory locality
  - Assign “home” node for each VM
  - Migrate VMs and pages across nodes
- VM migration
  - Move all VCPUs and threads associated with VM
  - Migrate to balance load, improve locality
- Page migration
  - Allocate new pages from home node
  - Remap PPNs from remote to local MPNs (migration)
  - Share MPNs per-node (replication)

NUMA Scheduling: Future Directions

- Better page migration heuristics
  - Determine most profitable pages to migrate
  - Some high-end systems (*e.g.* SGI Origin) had per-page remote miss counters
  - Not available on commodity x86 platforms
- Expose NUMA to guest?
  - Enable guest OS optimizations
  - Impact on portability

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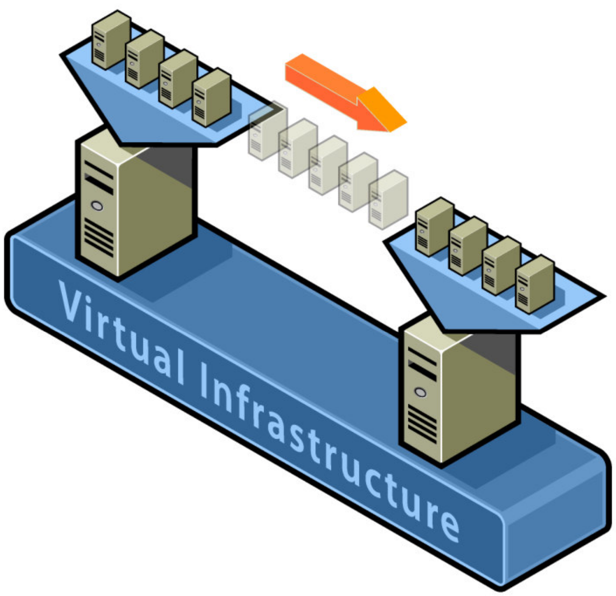
Distributed Systems

- Useful features
  - Choose initial host when VM powers on
  - Migrate running VMs across physical hosts
  - Dynamic load balancing
  - Support cloud computing, multi-tenancy
- Challenges
  - Migration decisions involve multiple resources
  - Resource pools can span many hosts
  - Appropriate migration thresholds
  - Assorted failure modes (hosts, connectivity, etc.)

VMware vMotion

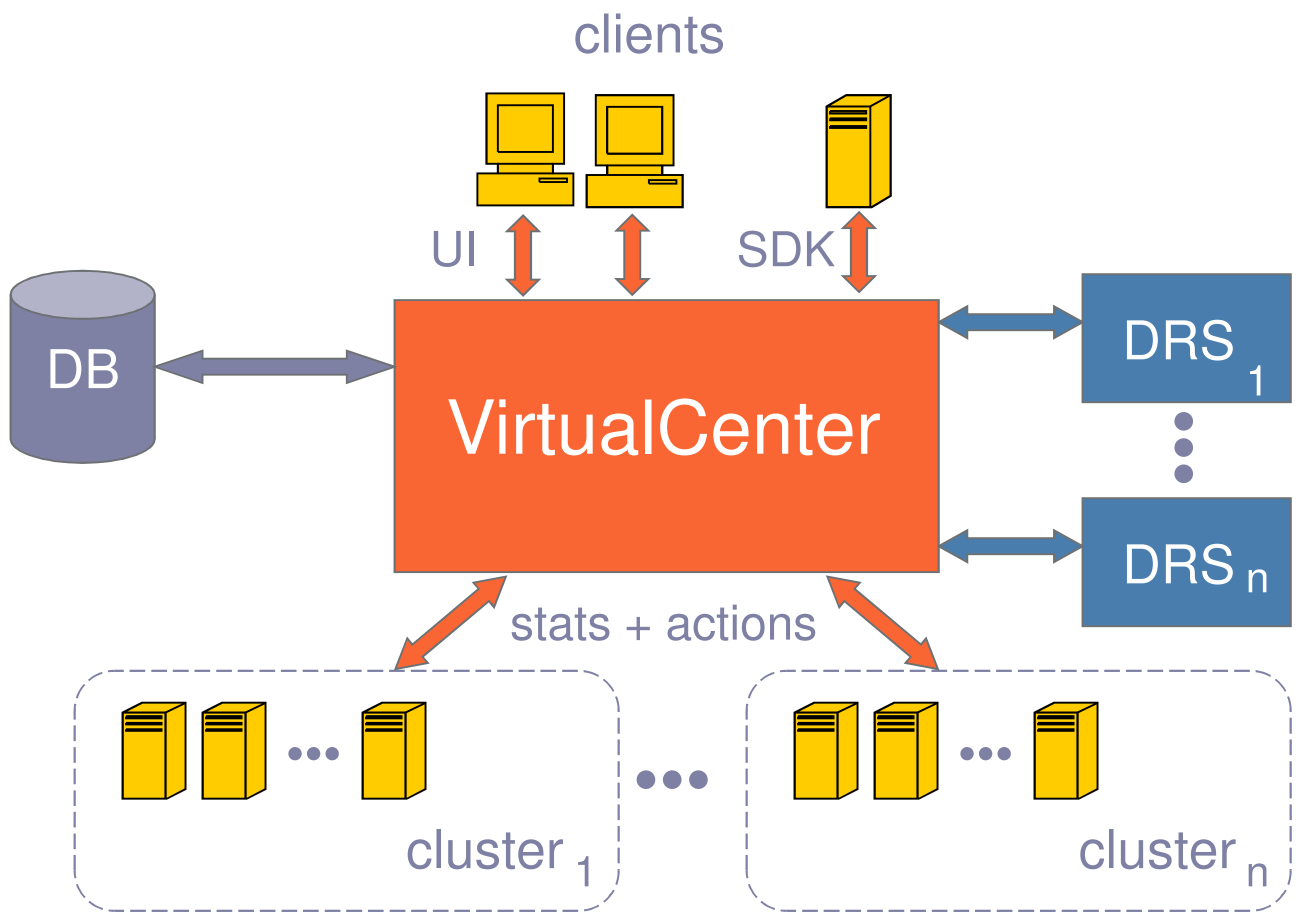


- "Hot" migrate VM across hosts
  - Transparent to guest OS, apps
  - Minimal downtime (sub-second)
- Requirements
  - Shared storage (e.g. SAN/NAS/iSCSI)
  - Same subnet (no forwarding proxy)
  - Compatible processors (EVC)
- Details
  - Track modified pages (write-protect)
  - Pre-copy step sends modified pages
  - Keep sending "diffs" until converge
  - Start running VM on destination host
  - Exploit meta-data (shared, swapped)

VMware DRS/DPM

- DRS = Distributed Resource Scheduler
- Cluster-wide resource management
  - Uniform controls, same as available on single host
  - Flexible hierarchical policies and delegation
  - Configurable automation levels, aggressiveness
  - Configurable VM affinity/anti-affinity rules
- Automatic VM placement
  - Optimize load balance across hosts
  - Choose initial host when VM powers on
  - Dynamic rebalancing using vMotion
- DPM = Distributed Power Management
  - Power off unneeded hosts, power on when needed again

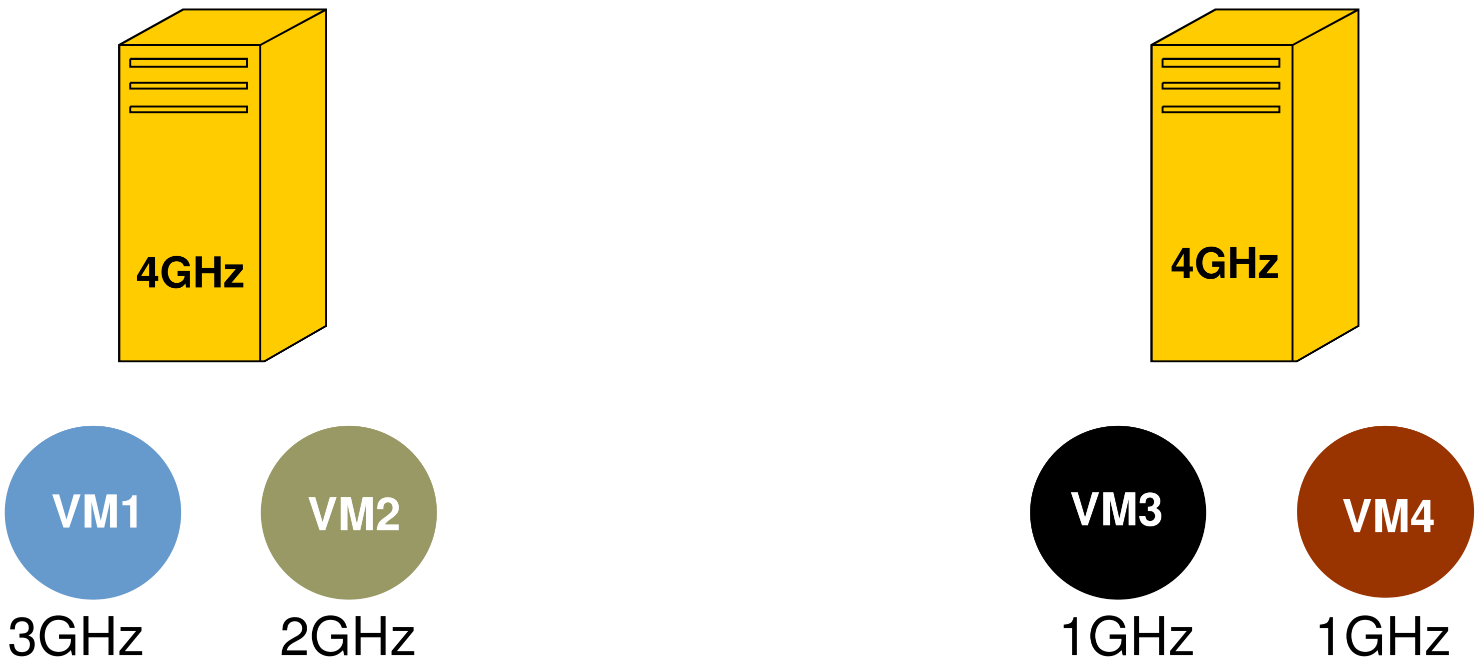
DRS System Architecture



DRS Balancing Details

- Compute VM entitlements
  - Based on resource pool and VM resource settings
  - Don’t give VM more than it demands
  - Reallocate extra resources fairly
- Compute host loads
  - Load ≠ utilization unless all VMs equally important
  - Sum entitlements for VMs on host
  - Normalize by host capacity
- Consider possible vMotions
  - Evaluate effect on cluster balance
  - Incorporate migration cost-benefit for involved hosts
- Recommend best moves (if any)

Simple Balancing Example



Host normalized entitlement = 1.25

Host normalized entitlement = 0.5

Recommendation: migrate VM2

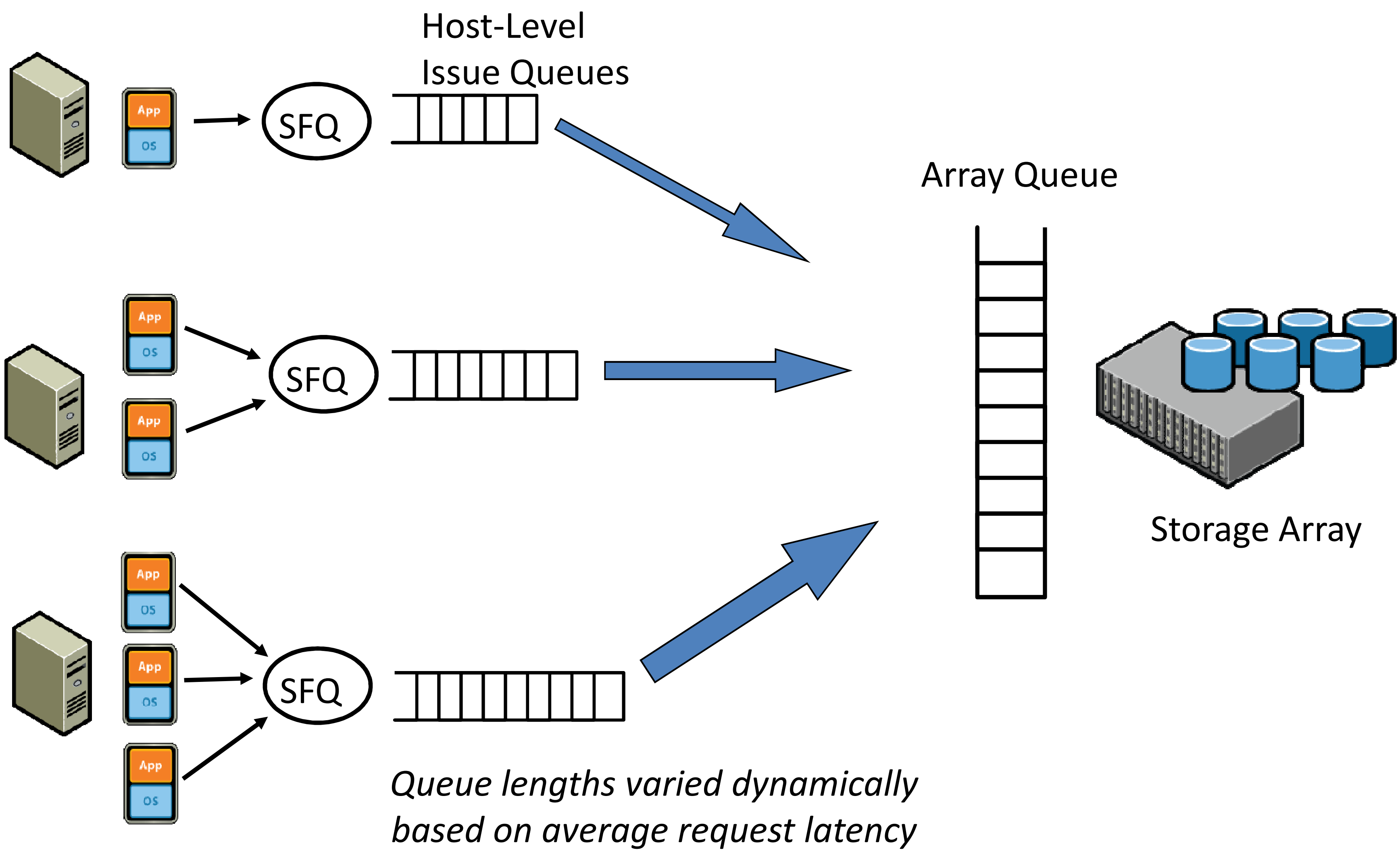
DPM Details (Simplified)

- Set target host demand/capacity ratio (63% $\pm$ 18%)
  - If some hosts above target range, consider power on
  - If some hosts below target range, consider power off
- For each candidate host to power on
  - Ask DRS “what if we powered host off and rebalanced?”
  - If more hosts within (or closer to) target, recommend action
  - Stop once no hosts are above target range
- For each candidate host to power off
  - Ask DRS “what if we powered host off and rebalanced?”
  - If more hosts within (or closer to) target, recommend action
  - Stop once no hosts are below target range

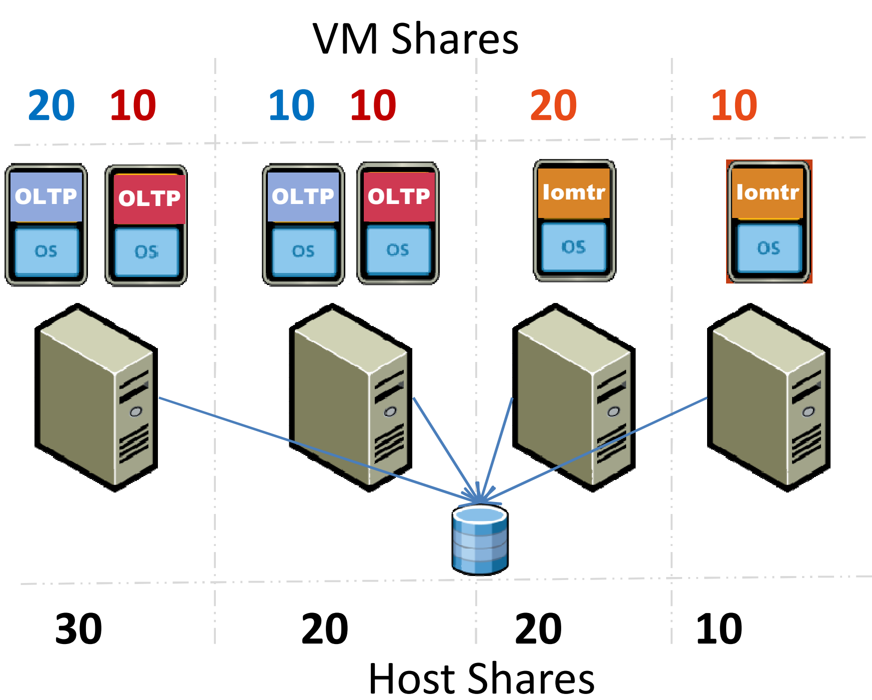
Distributed I/O Management

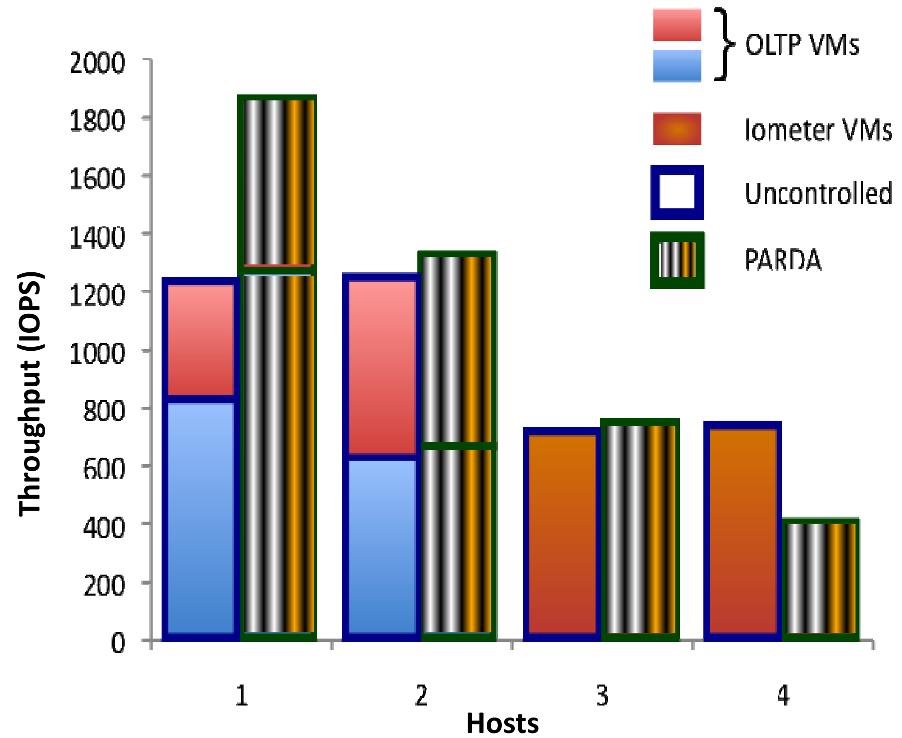
- Host-level I/O scheduling
  - Arbitrate access to local NICs and HBAs
  - Disk I/O bandwidth management (SFQ)
  - Network traffic shaping
- Distributed systems
  - Host-level scheduling insufficient
  - Multiple hosts access same storage array / LUN
  - Array behavior complex, need to treat as black box
  - VMware PARDA approach [Gulati et al. FAST ’09]

PARDA Architecture



PARDA End-to-End I/O Control





- Shares respected independent of VM placement
- Specified I/O latency threshold enforced (25 ms)

Distributed Systems: Future Directions

- Large-scale cloud management
- Virtual disk placement/migrations
  - Leverage “storage vMotion” as primitive
  - Storage analog of DRS
  - VMware BASIL approach [Gulati et al. FAST ’10]
- Proactive migrations
  - Detect longer-term trends
  - Move VMs based on predicted load

Summary

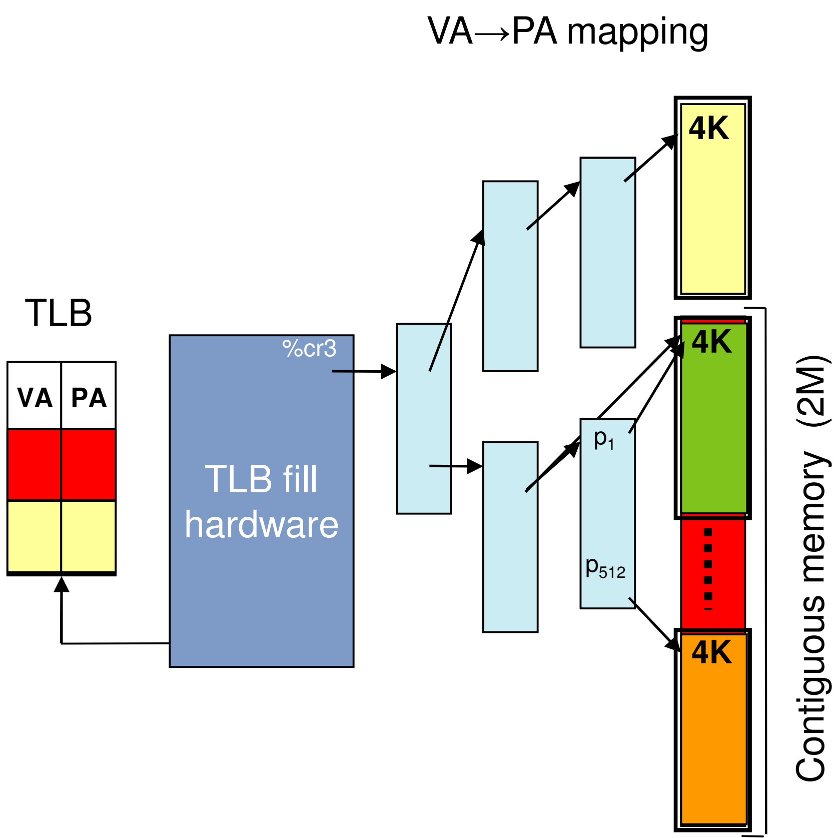
- Resource management
  - Controls for specifying allocations
  - Processor, memory, NUMA, I/O, power
  - Tradeoffs between multiple resources
  - Distributed resource management
- Rich research area
  - Plenty of interesting open problems
  - Many unique solutions

Backup Slides

CPU Resource Entitlement

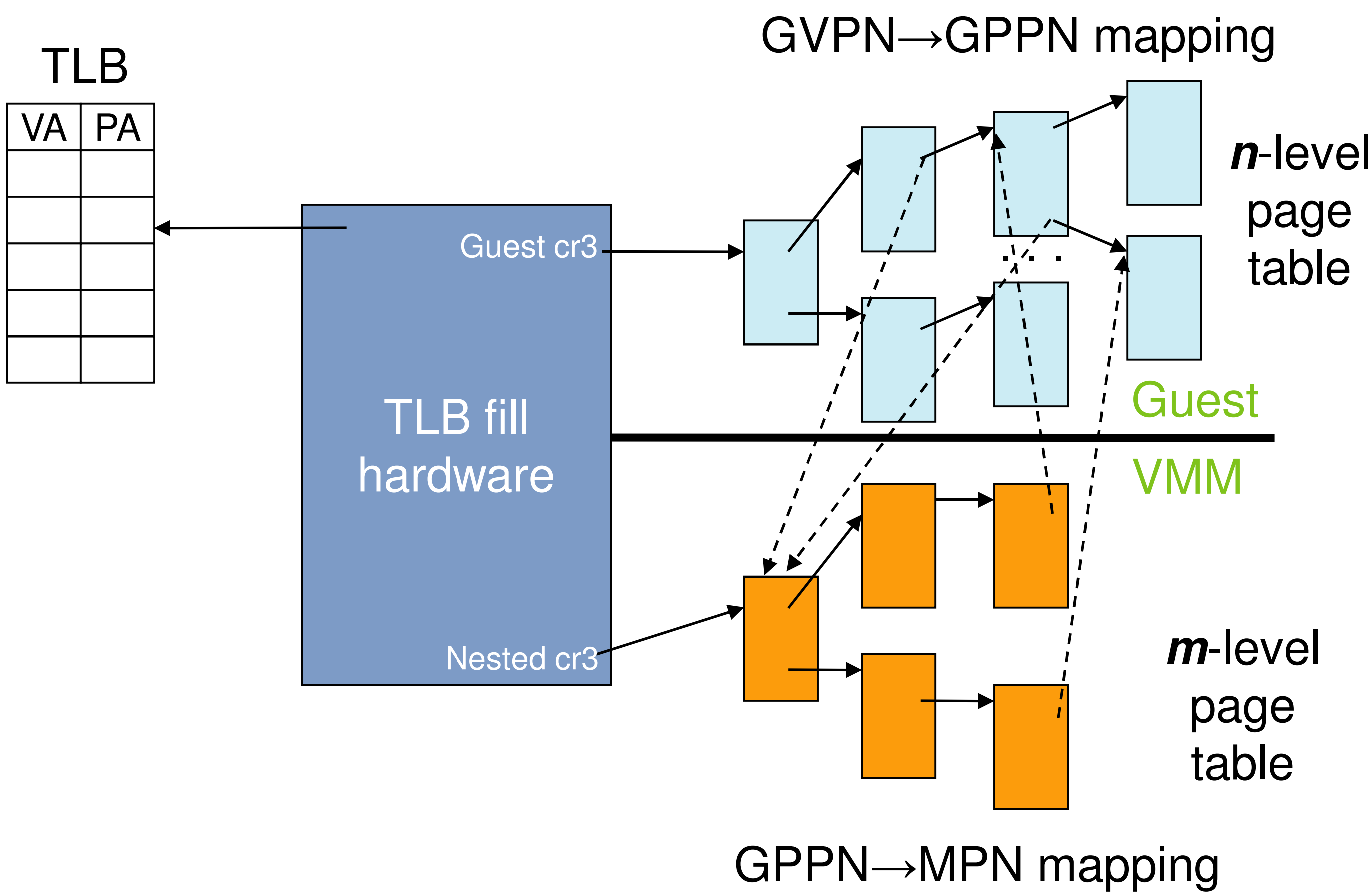
- Resources that each VM "deserves"
  - Combining shares, reservation, and limit
  - Allocation if all VMs full active (*e.g.* CPU-bound)
  - Concrete units (MHz)
- Entitlement calculation (conceptual)
  - Entitlement initialized to reservation
  - Hierarchical entitlement distribution
  - Fine-grained distribution (*e.g.* 1 MHz at a time), preferentially to lowest entitlement/shares
  - Don't exceed limit
- What if VM idles?
  - Don't give VM more than it demands
  - CPU scheduler distributes resources to active VMs
  - Unused reservations not wasted

Large Pages



- Small page (4 KB)
  - Basic unit of x86 memory management
  - Single page table entry maps to small 4K page
- Large page (2 MB)
  - 512 contiguous small pages
  - Single page table entry covers entire 2M range
  - Helps reduce TLB misses
  - Lowers cost of TLB fill

Nested Page Tables



Quadratic page table walk time, O(***n**** ***m***)