Xen and the Art of Virtualization *Revisited*

Ian Pratt, Citrix Systems Inc.

Outline

- A brief history of Xen
- Why virtualization matters
- Paravirtualization review
- Hardware-software co-design
  - MMU virtualization
  - Network interface virtualization
- The virtualization frontier

The Xen Story

- Mar 1999 XenoServers HotOS paper
- Apr 2002 Xen hypervisor development starts
- Oct 2003 Xen SOSP paper
- Apr 2004 Xen 1.0 released
- Jun 2004 First Xen developer's summit
- Nov 2004 Xen 2.0 released
- 2004 Hardware vendors start taking Xen seriously
- 2005 RedHat, Novell, Sun and others adopt Xen
- 2006 VMware and Microsoft adopt paravirtualization
- Sep 2006 First XenEnterprise released
- May 2008 Xen embedded in Flash on HP/Dell servers

Xen Project Mission

- Build the industry standard open source hypervisor
  - Core "engine" that is incorporated into multiple vendors' products
- Maintain Xen's industry-leading performance
  - Be first to exploit new hardware acceleration features
  - Help OS vendors paravirtualize their OSes
- Maintain Xen's reputation for stability and quality
  - Security must now be paramount
- Support multiple CPU types; big and small systems
  - From server to client to mobile phone
- Foster innovation
- Drive interoperability

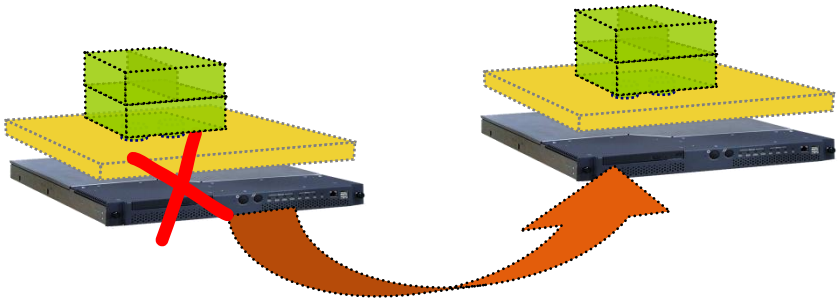
Why Virtualization is ‘Hot’

- Clearing up the mess created by the success of ‘scale-out’
  - One Application per commodity x86 server
  - Leads to ‘server sprawl’
  - 5-15% CPU utilization typical
- Failure of popular OSes to provide
  - Full configuration isolation
  - Temporal isolation for performance predictability
  - Strong spatial isolation for security and reliability
  - True backward app compatibility

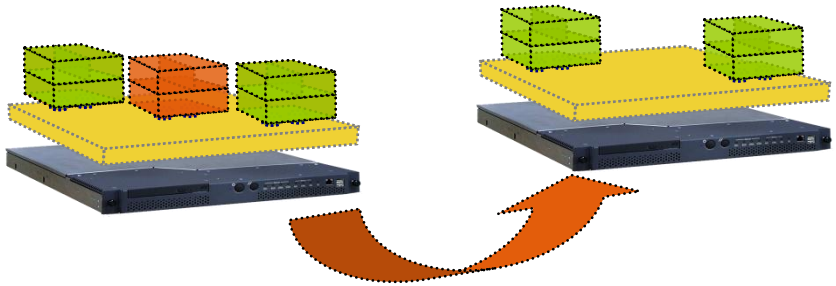
First Virtualization Benefits

- Server consolidation
  - Consolidate scale-out success
  - Exploit multi-core CPUs
- Manageability
  - Secure remote console
  - Reboot / power control
  - Performance monitoring
- Ease of deployment
  - Rapid provisioning
- VM image portability
  - Move image between different hardware
  - Disaster Recovery

2nd Generation Virtualization Benefits

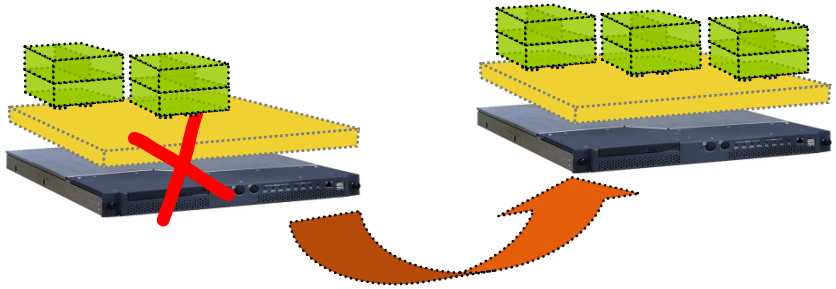


- **Avoid planned downtime with VM Relocation**

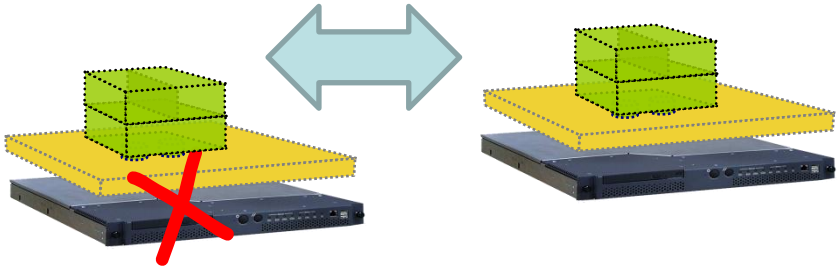


- **Dynamically re-balance workload to meet app SLAs or to saver power**

2nd Generation Virtualization Benefits



- ***Restart-HA*** **monitors hosts and VMs to keep apps running**



- ***Hardware Fault Tolerance*** **with deterministic replay or checkpointing**

Hypervisor Security

- “hidden hypervisor” attack is a myth, but exploitation of an installed hypervisor is a real and dangerous threat
- Hypervisors add more software and thus increase the attack surface
  - Network-facing control stack
  - VM containment
- Xen smaller and defensible than an OS
  - Need a “strength in depth” approach
    - Disaggregate, De-privilege, narrow interfaces
    - Xen Security Modules from the NSA
  - Measured launch

Improving Security with Hypervisors

- Hypervisors allow administrative policy enforcement from outside of the OS
  - Firewalls, IDS, malware scanning etc
    - More robust as not so easily disabled
    - Provides protection within a network rather than just at borders
  - Hardening OSes with immutable memory, taint tracking, logging and replay
  - Backup policy, multi-path IO, HA, FT etc
    - Availability and Reliability
- Reducing human effort required to admin all the VMs is the next frontier

Breaking the bond between OS and h/w

- Simplifies Application-stack certification
  - Certify App-on-OS; OS-on-HV; HV-on-h/w
  - Enables Virtual Appliances
- Virtual hardware greatly reduces the effort to modify/create new OSes
  - Application-specific OSes
    - Slimming down and optimization of existing OSes
    - “Native execution” of Apps
- Hypervisors enable h/w vendors to ‘light up’ new features more rapidly

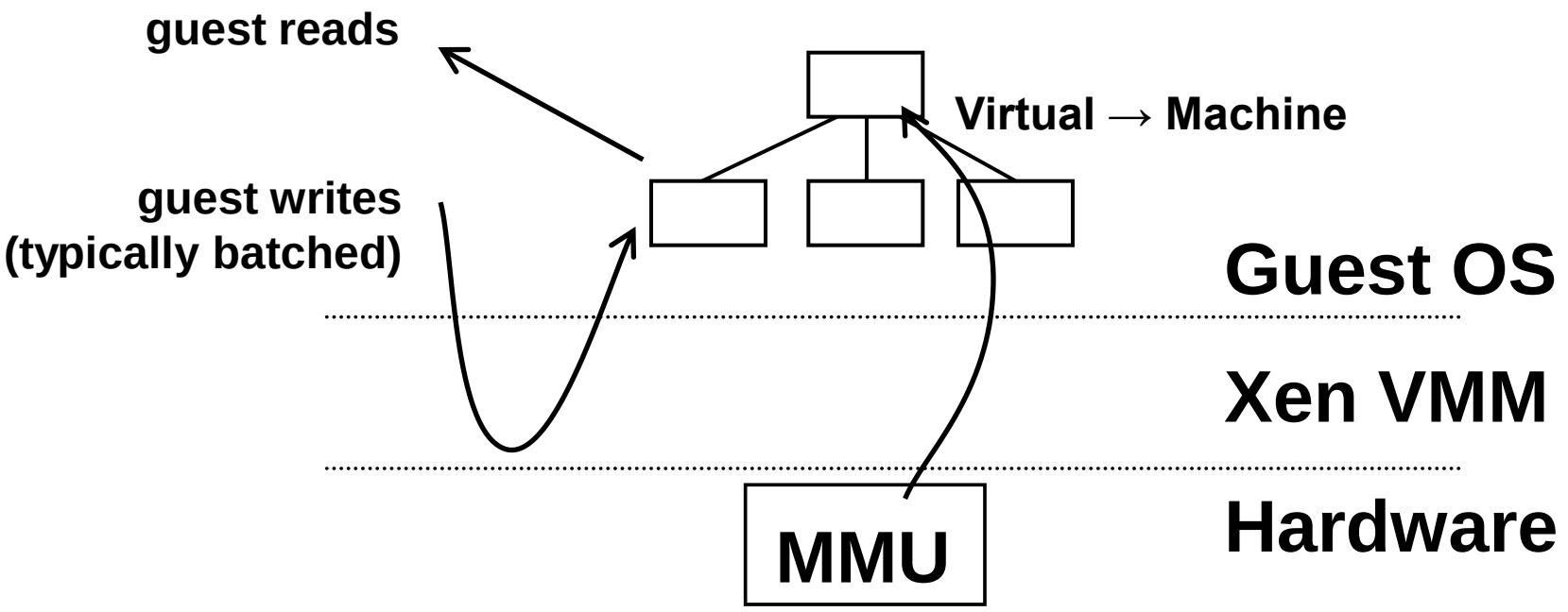
Paravirtualization

- Extending the OS to be aware it is running in a virtualized environment
  - For performance and enhanced correctness
  - IO, memory size, CPU, MMU, time
- In Xen <2.0, some paravirtulizations were compulsory to close x86 virtualization holes
  - Intel VT / AMD-V allow incremental paravirtualization
- Paravirtualization is still very important for performance, and works along side enhancements to the hardware
  - Higher-level paravirtualizations yield greatest benefit

MMU Virtualization

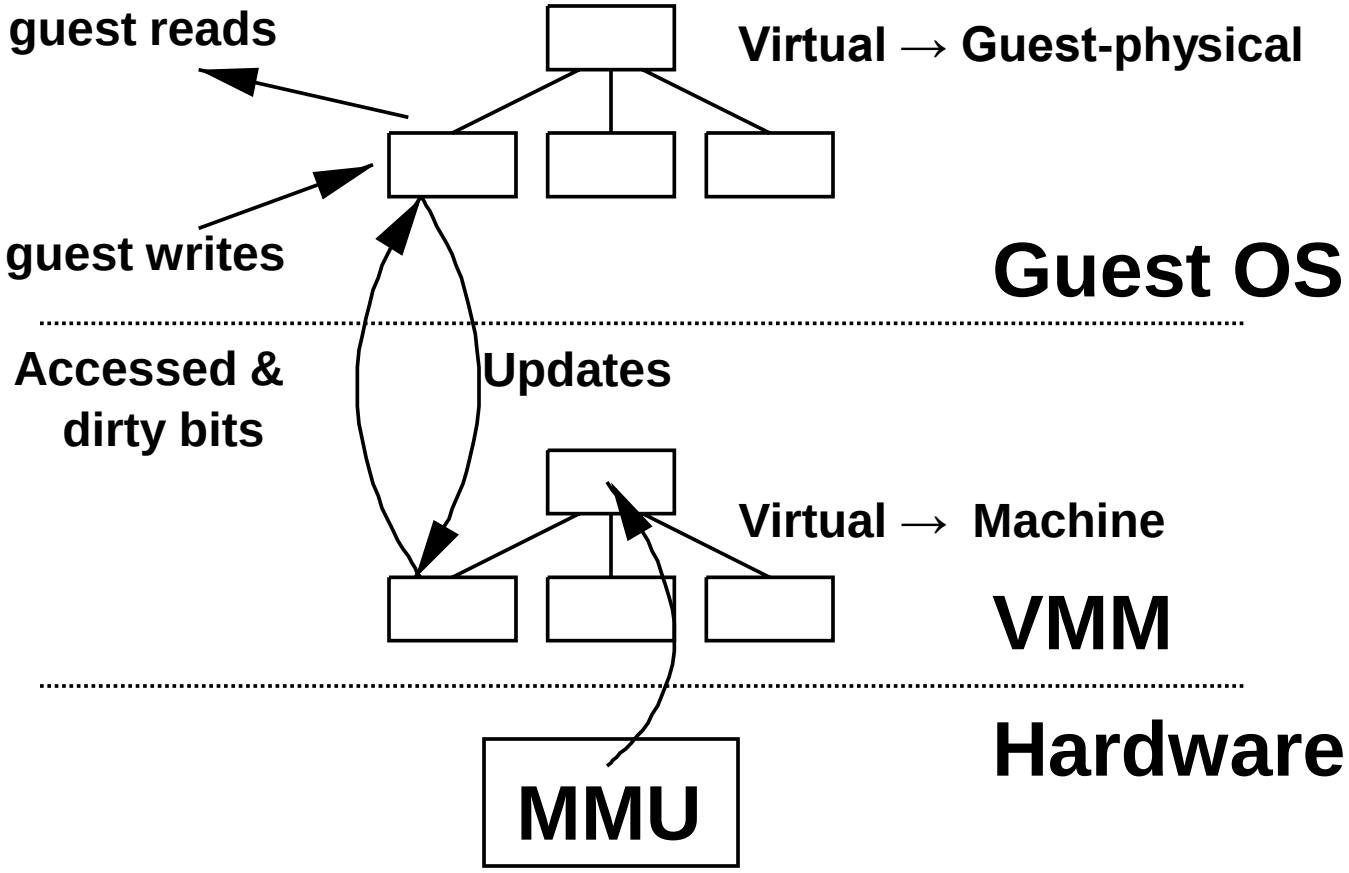
- Critical for performance, challenging to make fast, especially SMP
  - Hot-unplug unnecessary virtual CPUs
  - Use multicast TLB flush paravirtualizations etc
- Xen supports 3 MMU virtualization modes
  1. Direct pagetables
  2. Shadow pagetables
  3. Hardware Assisted Paging
- OS Paravirtualization compulsory for #1, optional (and very beneficial) for #2&3

MMU Virtualization : Direct-Mode



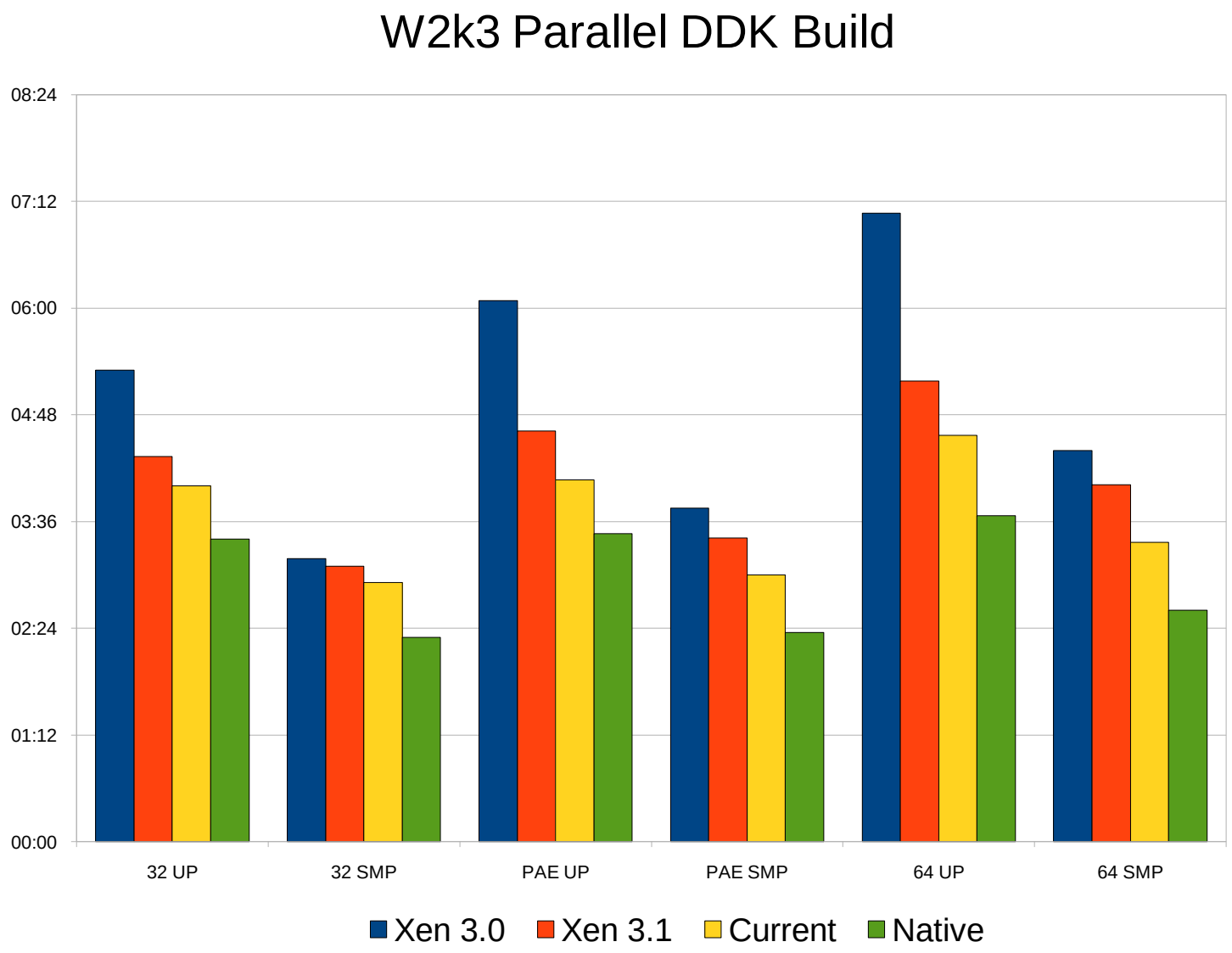
- Requires guest changes
  - Supported by Linux, Solaris, FreeBSD, NetBSD etc
- Highest performance, fewest traps

Shadow Pagetables



- Guest changes optional, but help with batching, knowing when to unshadow
- Latest algorithms work remarkably well

Peformance


W2k3 Parallel DDK Build
08:24
07:12
06:00
04:48
03:36
02:24
01:12
00:00
32 UP
32 SMP
PAE UP
PAE SMP
64 UP
64 SMP
Xen 3.0
Xen 3.1
Current
Native

Hardware Assisted Paging

- AMD NPT / Intel EPT
- Hardware handles translation with nested pagetables
  - guest PTs managed by guest in normal way
  - guest-physical to machine-physical tables managed by Xen
- Can increases the number of memory accesses to perform a TLB fill pagetable walk by factor of 5
  - Hopefully less through caching partial walks
  - But reduces the effective TLB size
- Current implementations often perform worse than shadow PTs
  - Wide-SMP guests do relatively better due to no s/w locking
    - TLB flush paravirtualizations essential
  - Hardware will improve: TLBs will get bigger, caching more elaborate, prefetch more aggressive

Network Interface Virtualization

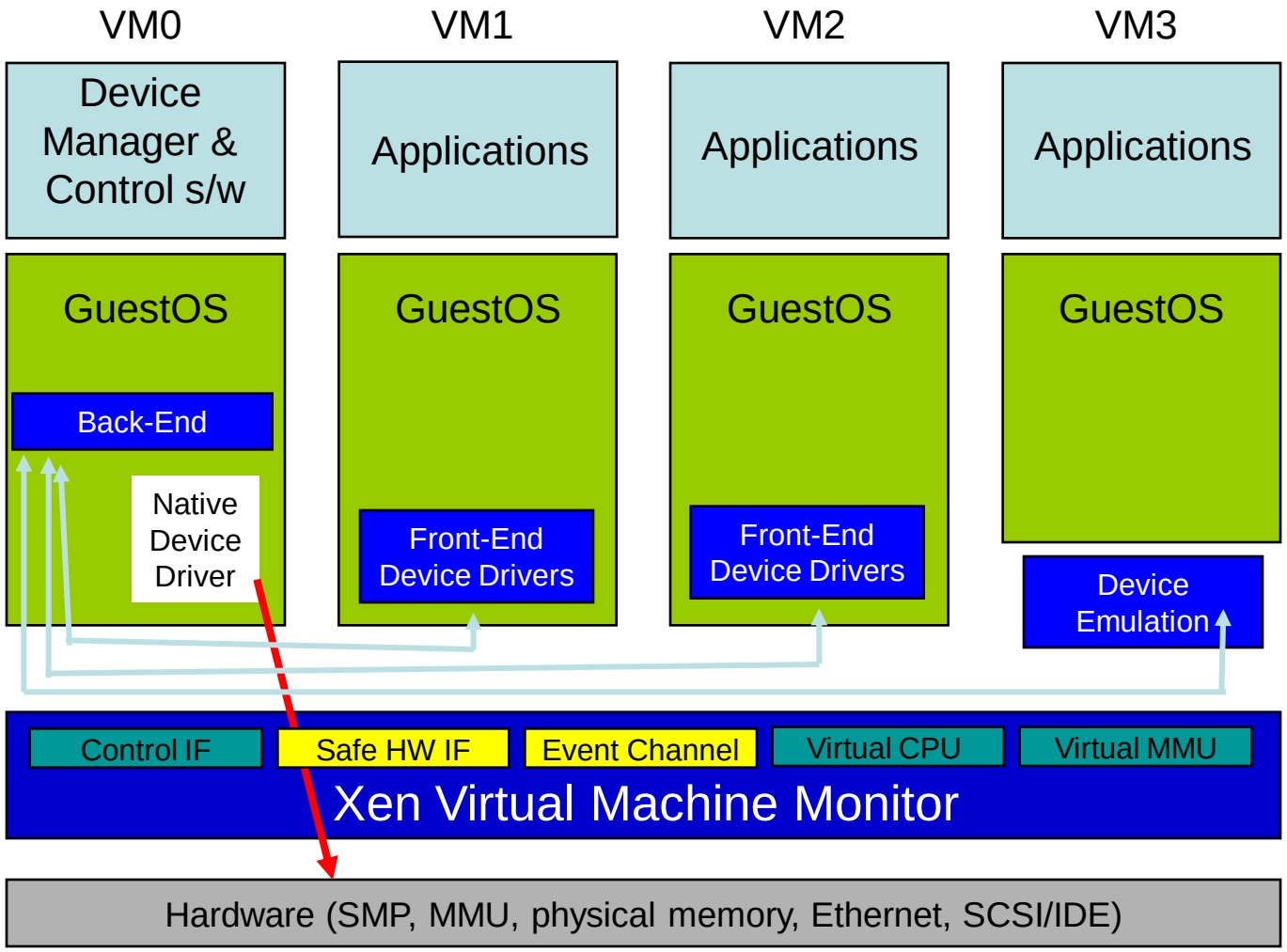
- Network IO is tough
  - High packet rate
    - Batches often small
  - Data must typically be copied to VM on RX
  - Some apps latency sensitive
- Xen's network IO virtualization has evolved over time
  - Take advantage of new NIC features
  - Smart NIC categorization: Types 0-3

Level 0 : Modern conventional NICs

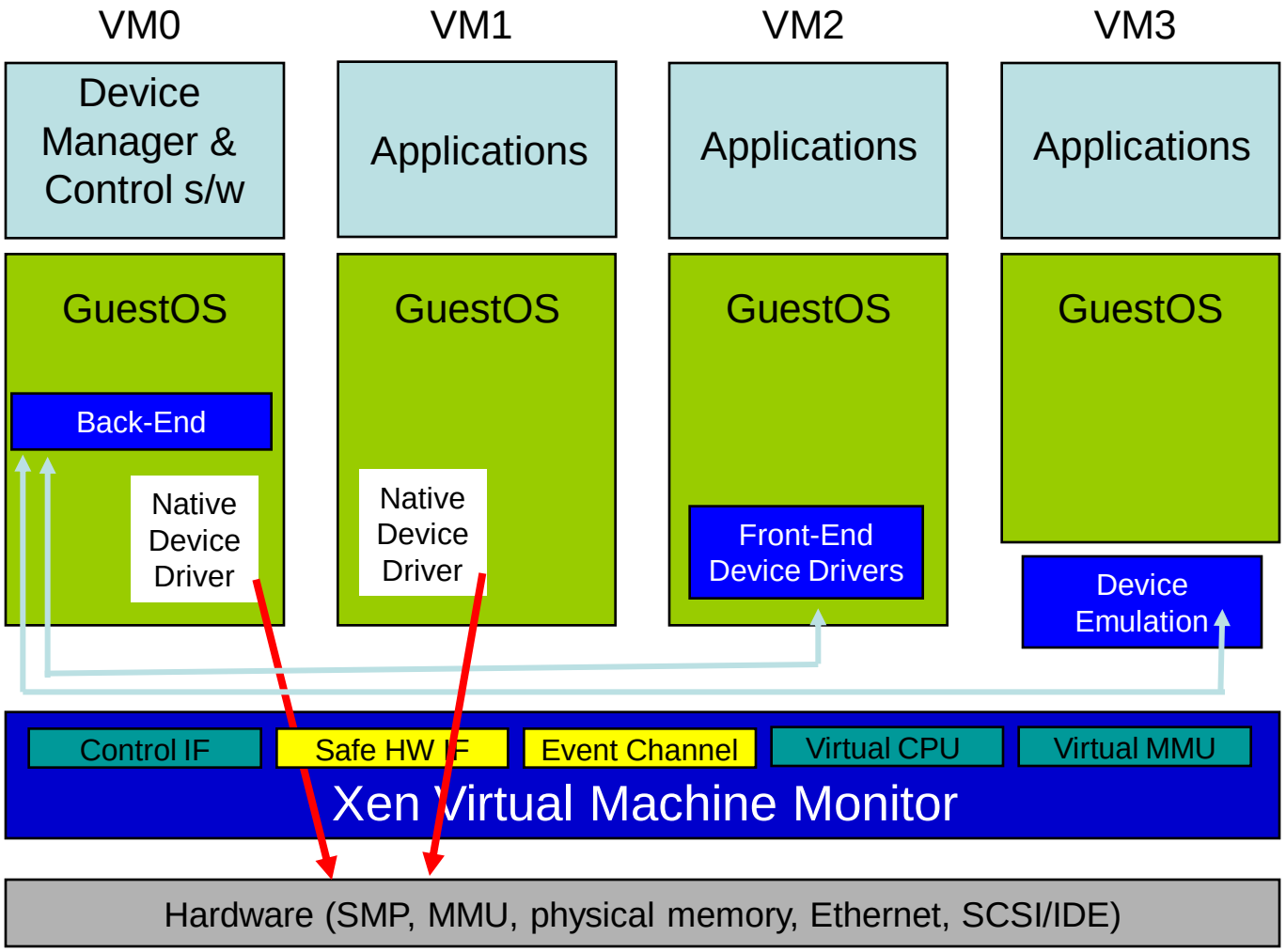
- Single free buffer, RX and TX queues
- TX and RX checksum offload
- Transmit Segmentation Offload (TSO)
- Large Receive Offload (LRO)
- Adaptive interrupt throttling
- MSI support

- (iSCSI initiator offload – export blocks to guests)
- (RDMA offload – helps live relocation)

I/O Architecture



Direct Device Assignment



Level 1 : Multiple RX Queues

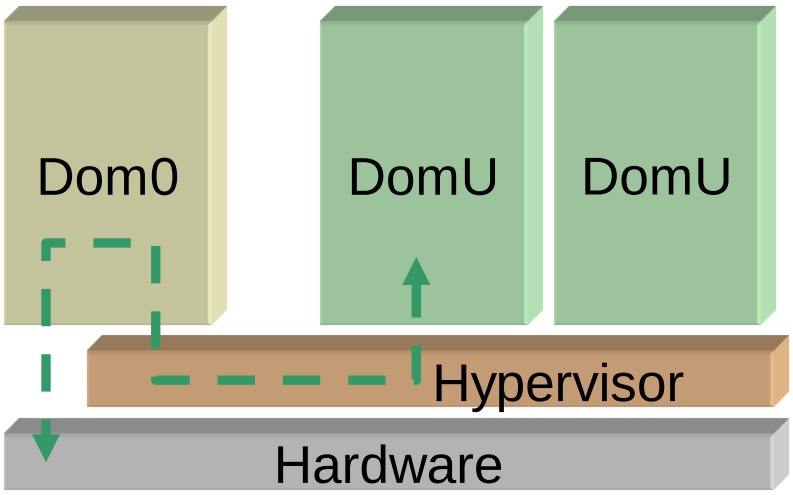
- NIC supports multiple free and RX buffer Q's
  - Choose Q based on dest MAC, VLAN
  - Default queue used for mcast/broadcast
- Great opportunity for avoiding data copy for high-throughput VMs
  - Try to allocate free buffers from buffers the guest is offering
  - Still need to worry about bcast, inter-domain etc
- Multiple TX queues with traffic shapping

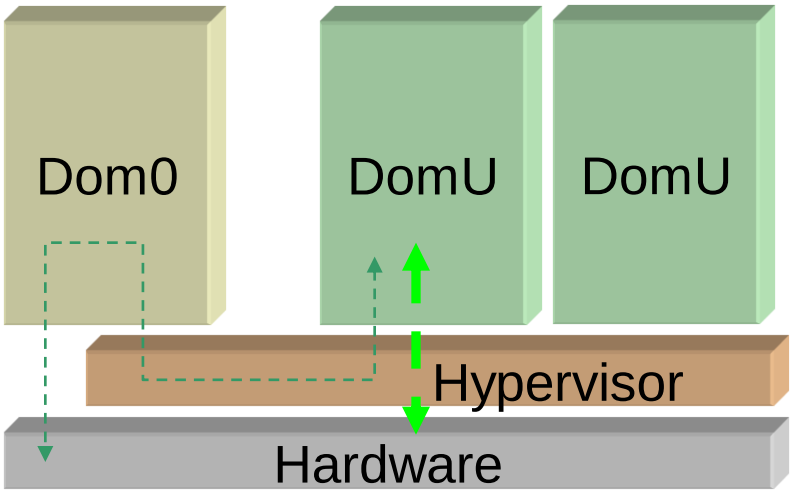
Level 2 : Direct guest access

- NIC allows Q pairs to be mapped into guest in a safe and protected manner
  - Unprivileged h/w driver in guest
  - Direct h/w access for most TX/RX operations
  - Still need to use s/w path for bcast, inter-dom
- Memory pre-registration with NIC via privileged part of driver (e.g. in dom0)
  - Or rely on architectural IOMMU in future
- For TX, require traffic shaping and basic MAC/srcIP filtering enforcement

Level 2 NICs e.g. Solarflare / Infiniband

- Accelerated routes set up by Dom0
  - Then DomU can access hardware directly
- Allow untrusted entities to access the NIC without compromising system integrity
  - Grant tables used to pin pages for DMA
- Treated as an “accelerator module” to allow easy hot plug/unplug



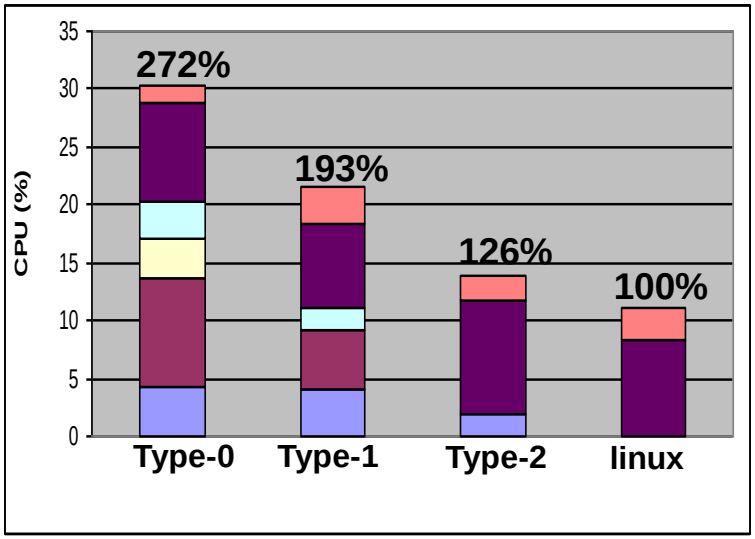


Level 3 Switch on NIC / SR-IOV

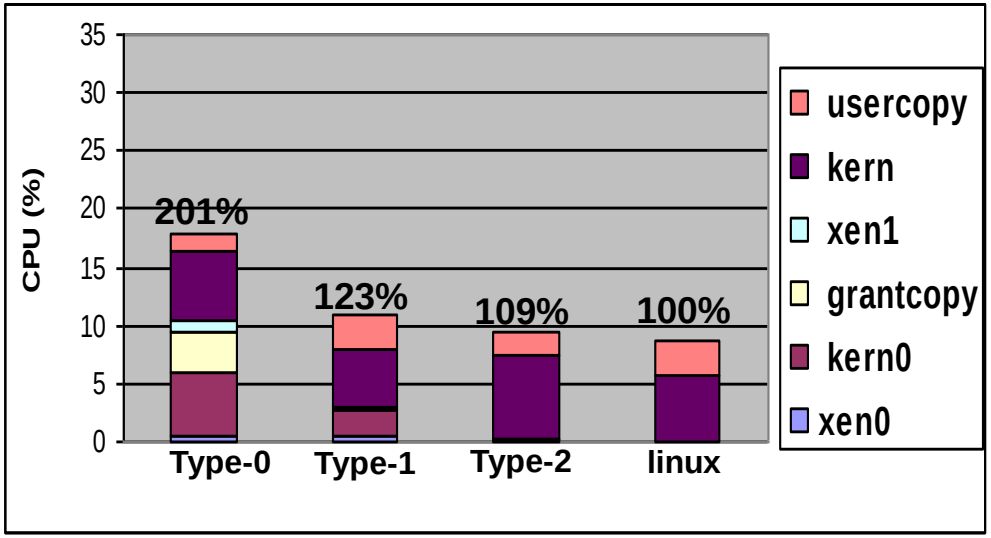
- NIC presents itself as multiple PCI devices, one per guest
  - Relies on IOMMU for protection
  - Still need to deal with the case when there are more VMs than virtual h/w NIC
  - Worse issue with h/w-specific driver in guest
- Full L2+ switch functionality on NIC
  - Inter-domain traffic can go via NIC
    - But goes over PCIe bus twice

Performance

Default configuration (6 pkt/intr)



Interrupt throttling config (64 pkt/intr)



- Smarter NICs reduce CPU overhead substantially
- Care must be taken with type-2/3 NICs to ensure benefits of VM portability and live relocation are not lost
- “Extreme late copy” for zero-copy inter-domain communication under development

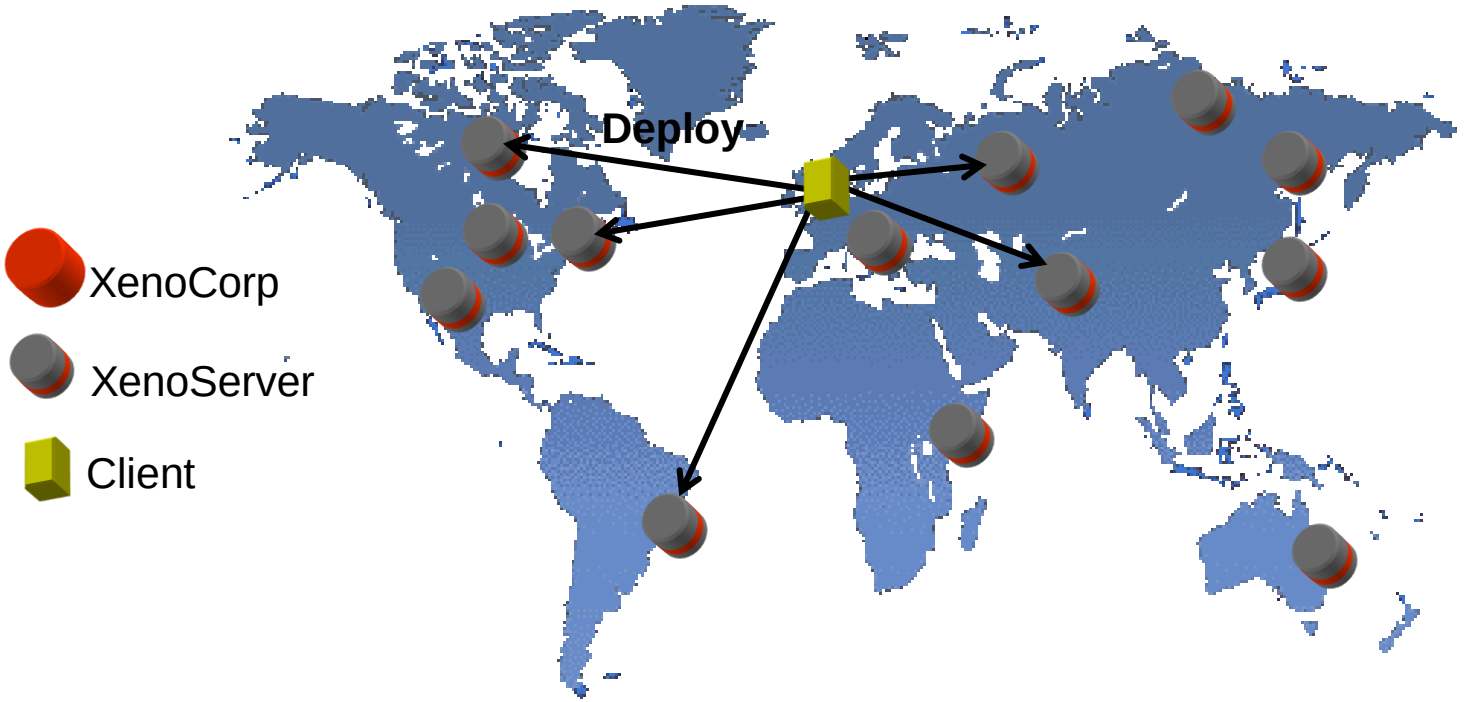
Xen Client : A Hypervisor for Client Devices

- Security, Manageability and Supportability
- “Embedded IT” virtual appliances
  - IDS, Malware detection, remote access, backup etc.
- Building Multi-level secure systems
  - Run multiple guest VMs with very controlled information flow
    - Enables Bring-Your-Own-PC model
    - Corporate VM; VM for web browsing; VM for banking
    - Seamless merging of VM displays
    - Migration of VMs between datacentre and laptops for offline use
- Security requires a true hypervisor architecture
  - Intel TXT / AMD SKINIT and Trusted Platform Module

From Laptops to Mobiles

- Smart phones and PDAs
  - Xen ARM
  - Smart phones now suffer from many of the same problems as PCs
- Simple restricted use cases:
  - Three VMs running on one CPU:
    - Real time VM for controlling the radio
    - VM for vendor/operator -supplied s/w
    - VM for user-downloaded software

XenoServers : University Project from 1999



- Incremental rollout
- Flexible platform
- Unified management

- Global services and apps
- Exploit network topology
- Open commercial platform

Augmenting IT infrastructure with Cloud

- Dynamic infrastructure as a service
  - 100% virtualized, and fully manageable
  - Pay as you use - no long-term contracts
- Enterprise - Cloud Bridge
  - Optimize VM image deployment
  - Secure gateway between Cloud and Enterprise
- Initial applications for Cloud
  - End-user facing applications (e.g. Web) - take advantage of Cloud's global presence and fat pipes
  - Test and Dev environments, Disaster Recovery

Conclusions

- Open Source is a great way to get impact from University research projects
- Hypervisors will become ubiquitous, near zero overhead, built in to the hardware
- Virtualization may enable a new "golden age" of operating system diversity
- Virtualization is a really fun area to be working in!

ian.pratt@xen.org