Hypervisors & CPU Virtualization

ECE 650
Systems Programming & Engineering
Duke University, Spring 2016

But first a note on the midterm…

- In class next Thursday, 3/3
- Expect about a handful of questions (5-6ish)
  - Each question will require working through an exercise
  - Focus on topics we've covered in assignments
  - Focus on topics we've covered in more detail in lecture
- Closed Notes, but…
  - You may bring and use 1 crib sheet during the midterm
  - Single piece of paper (no bigger than 8.5" x 11"), front and back
  - No magnification devices ☺
  - Useful as a study tool, to help you focus on the important topics

Midterm Topics

- Concurrency & Synchronization
  - Process vs. Thread
  - Concurrent programming, race conditions, mutual exclusion, synchronization
- IPC
  - Shared memory vs. Message passing
  - Mmap for shared memory across different processes
  - UNIX FIFOs and Pipes for messaging
- User Space ⇔ Kernel interaction
  - System Calls
  - Interrupt mechanism
  - Dynamic memory management routines (malloc & free)
- Process Management & CPU Scheduling
  - Process State & Process Control Block
  - CPU scheduling algorithms

Midterm Topics (2)

- Protection & Security
  - Difference between the two
  - Access Matrix
  - Types of security threats (viruses, trojans, etc.)
- I/O Systems and I/O Operation
- File Systems
  - File System Directory
  - Disk allocation
- Virtual Memory Management
  - Virtual vs. physical address
  - Paging & page table architecture
  - OS page replacement
- Virtualization & Hypervisors

And next, an Assignment #2 Note

- I neglected to specify one very tricky requirement!
  - But without it, we could not properly test your rootkit
- Please add the following line of code at the beginning of your sneaky_process.c main() function:
  - printf("sneaky_process pid=%d\n", getpid());
- Needed to know which process ID should be hidden

Overview of Virtualization

- We've discussed a form of virtualization
  - Provided by the OS to user level programs / processes
  - Programs written as if they have full access to an entire machine
    - Resources: memory, disk, I/O, CPU
    - User processes typically do not need to care or know that these resources are in fact shared (concurrently or time-sliced) with others
- We can extend this to the OS
  - Support multiple OS instances (guest OSes) running on a CPU
  - Can be multiple instances of same OS or different OSes
  - Typically, guest OSes run on top of new software layer
    - Called Hypervisor (or VMM, Virtual Machine Monitor)
    - Sits between the guest OSes and CPU hardware in SW stack
  - Very useful for workload consolidation

Xen

- "Xen and the Art of Virtualization"
- Xen is a hypervisor
- Has evolved into a widely used one to support virtualization
  - For x86 and ARM
  - IBM SoftLayer, Amazon EC2, Rackspace Cloud
- Now supported in many different forms
  - We'll discuss the fundamental principles described in the paper

VM Challenges

- Need to partition machine to support concurrent execution of multiple operating systems

1. Virtual machines must be isolated from each other
   - For protection
   - So that performance of one does not affect performance of another
2. Must support a variety of different OSes
   - To enable workload consolidation
3. Performance overhead should be small
   - User applications should not slow down (much)

Xen Approach

- Two main approaches to virtualization
  - Full Virtualization:
    - A virtual SW interface to all machine HW is exposed by VMM
    - Guest OS cannot access hardware directly
    - Advantages: can support unmodified guest OSes
    - Disadvantages: performance (all guest OS-HW interaction goes through VMM)
  - Paravirtualization:
    - This is what Xen uses
    - Exposes HW to the guest OSes where it is critical for performance
    - Exposed virtual SW interface to machine HW otherwise
    - Advantages: less slowdown for user applications
    - Disadvantages: requires some OS modification (but not to apps)
      - Supports same Application Binary Interface (ABI)

Definitions

- Guest OS
  - Refers to one of the OSes that can be hosted on the Xen VMM
- Domain
  - A running instance of a VM within which a guest OS executes
- Think of as analogous to program vs. process
  - Static vs. dynamic

Paravirtualized x86 Interface

- 3 main aspects of the paravirtualized interface
  - Memory management
    - Segmentation, Paging
  - CPU
    - Protection, Exceptions, System Calls, Interrupts, Time
  - Device I/O
    - Network, Disk, etc.
- We've covered each of these 3
  - From the perspective of OS management
  - While all details mentioned in the paper may not be clear, the general concepts should seem familiar

Memory Management Interface

- This is the difficult part of paravirtualization
- Centers around TLB & page table management
- Two types of TLB
  - SW managed:
    - TLB miss traps to privileged SW; loads new entry from page tables
    - TLB entries tagged with address space IDs to avoid flushing the TLB when moving from CPU execution of one OS to another
  - HW managed (what x86 has):
    - HW in the processor handles TLB misses by "page table walk"
    - No address space IDs
      - Requires TLB flush on every address space switch

Memory Management Interface (2)

- How does Xen do it?
  - Guest OSes do allocation and management of HW page tables
    - Xen is minimally involved to ensure OS safety and isolation
    - Guest OS can only map to memory it owns (physical frames)
    - When a new page table is required (e.g. a process is created):
      - Guest OS allocates & initializes a page that it owns
      - Registers this page with Xen (Xen validates the page table info)
      - Write permission to this page are removed from the guest OS
  - Xen is mapped into top 64MB of every address space
    - No TLB flush required when entering / exiting the VMM

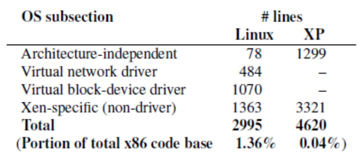
CPU

- 4 privilege levels are supported in x86
  - Referred to as ring 0 - ring 3 (from highest to lowest priority)
  - Normally, the OS runs in ring 0, user process in ring 3
  - Xen downgrades OS privilege to ring 1; Xen runs in ring 0
- Privileged instructions executed by the OS now fault and trap into the VMM (can only be executed within ring 0)
- Exceptions handled in straightforward way
  - Guest OS registers a table of exception handlers with Xen
  - When HW events occur requiring exception handling, Xen returns control to appropriate exception handler
- Special care for performance-sensitive exceptions:
  - System calls and page faults
  - "Fast handler" installed which is directly accessed by CPU
    - No need to pass through Ring 0 VMM first

Device I/O

- Xen exposes a set of simple device abstractions
- I/O data is transferred between a domain & Xen
  - Via ring buffers
  - In asynchronous manner
- Lightweight event mechanism used to notify domains
  - E.g. of I/O completion or data availability

Porting Effort

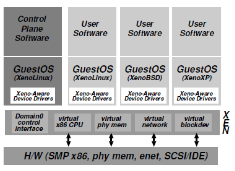


OS subsection	# lines Linux	# lines XP
Architecture-independent	78	1299
Virtual network driver	484	–
Virtual block-device driver	1070	–
Xen-specific (non-driver)	1363	3321
Total	**2995**	**4620**
(Portion of total x86 code base	**1.36%**	**0.04%)**

Table 2: The simplicity of porting commodity OSes to Xen. The cost metric is the number of lines of reasonably commented and formatted code which are modified or added compared with the original x86 code base (excluding device drivers).

Control & Management

- Separate policy vs. mechanism
  - Xen VMM implements mechanism (mostly)
  - Management control software handles policy
    - Running on a Guest OS
- Domain0 hosts app-level management SW
- Control Interface:
  - Create & Terminate domains
  - Partition physical resources
    - Across domains
    - CPU, physical memory, disk, .

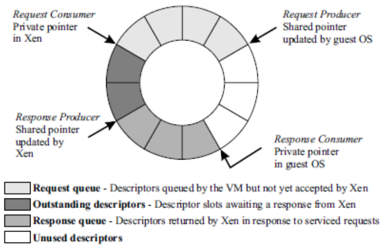


Xen ⇔ Guest OS Interaction

- Hypercalls: From a domain to Xen
  - Synchronous trap calls for service from a domain to Xen
  - Analagous to a system call from user process to OS
  - E.g. request page table updates
- Events: From Xen to a domain
  - Asynchronous notifications to a domain from Xen
  - Replaces device interrupts to an OS
  - Uses mechanism similar to UNIX signals (recall, like SW interrupts)
  - Pending events stored in a per-domain bitmask
  - Xen updates bit mask & invokes an event-callback handler specified by a guest OS
  - Guest OS handles events & resets bits

I/O Data Transfer

- Domains allocate shared buffers for device I/O


Request Consumer
Private pointer in Xen
Request Producer
Shared pointer updated by guest OS
Response Producer
Shared pointer updated by Xen
Response Consumer
Private pointer in guest OS
Request queue - Descriptors queued by the VM but not yet accepted by Xen
Outstanding descriptors - Descriptor slots awaiting a response from Xen
Response queue - Descriptors returned by Xen in response to serviced requests
Unused descriptors

CPU Scheduling

- Schedules domains on the CPU
  - According to some set policy to set allocation per domain
  - Uses a scheduling algorithm called Borrowed Virtual Time
- Per-domain scheduling parameters can be adjusted by the management software running in Domain0

Time and Timers

- Xen provides 3 views of time to domains
  - Real time
    - ns since machine boot time
  - Virtual time
    - A time that advances only while domain is executing
    - Can be used by guest OS to ensure it gets correct timeshare
  - Wall clock
    - Offset added to current real time
- Guest OS can program pair of alarm timers
  - One for real time and one for virtual time
  - Can use Xen-provided alarm timers to trigger earliers timeout
    - Via event mechanism

Virtual Address Translation

- Full virtualization exposes shadow page table to guest OS
  - Guest OS updates trap to VMM
  - Hardware events that update PT (e.g. 'accessed' or 'dirty' bits) require propagation up to shadow page tables of guest OS
  - Performance overhead!
- Guest OS registers page tables
  - Guest OS then has read-only access
  - Page table updates must be validated by Xen
    - Can be batched and sent to Xen via a single hypercall

Evaluation

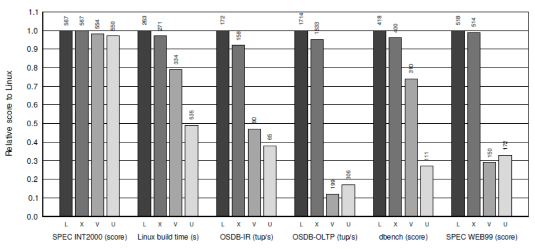


Figure 3: Relative performance of native Linux (L), XenoLinux (X), VMware workstation 3.2 (V) and User-Mode Linux (U).