Virtualization

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April 10, 2009

Synchronization

- Memorial service for Timothy Wismer
  - Friday, April 17
  - 16:00-18:00
  - Breed Hall (Margaret Morrison 103)
    - Sign will say "Private Event"
  - Donations to National Arthritis Foundation will be welcome

Outline

- Introduction
- Virtualization
- x86 Virtualization
- Paravirtualization
- Alternatives for Isolation
- Alternatives for “running two OSes on same machine”
- Summary

What is Virtualization?

- **Virtualization:**
  - **Process of presenting and partitioning computing resources in a *logical* way rather than partitioning according to *physical* reality**
- **Virtual Machine:**
  - **An execution environment (logically) identical to a physical machine, with the ability to execute a full operating system**
- **The *Process* abstraction is related to virtualization: it's at least similar to a physical machine**

Process : Kernel :: Kernel : ?

Advantages of the Process Abstraction

- Each process is a pseudo-machine
- Processes have their own registers, address space, file descriptors (sometimes)
- Protection from other processes

Disadvantages of the Process Abstraction

- **Processes share the file system**
  - **Difficult to simultaneously use different versions of:**
    - **Programs, libraries, configurations**
- **Single machine owner:**
  - **root *is* the superuser**
  - **Any process that attains superuser privileges controls all processes**
    - **Other processes aren't so isolated after all**

Disadvantages of the Process Abstraction

- Processes share the same kernel
  - Kernel/OS specific software
  - Kernels are *huge*, lots of possibly buggy code
- Processes have limited degree of protection, even from each other
  - OOM (out of memory) killer (in Linux) frees memory when all else fails

Why Use Virtualization?

- "Process abstraction" at the ***kernel*** layer
  - Separate file system
  - Different machine owners
- Offers much better protection (in theory)
  - Secure hypervisor, fair scheduler
  - Interdomain DoS? Thrashing?
- Run two operating systems on the same machine!

Why Use Virtualization?

- Huge impact on enterprise hosting
  - No longer need to sell whole machines
  - Sell machine slices
  - Can put competitors on the same physical hardware
    Can separate instance of VM from instance of hardware
- Live migration of VM from machine to machine
  - No more maintenance downtime
- VM replication to provide fault tolerance
  - "Why bother doing it at the application level?"

Disadvantages of Virtual Machines

- Attempt to solve what really is an abstraction issue somewhere else
  - Monolithic kernels
  - Not enough partitioning of global identifiers
    - pids, uids, etc
  - Applications written without distribution and fault tolerance in mind
- Provides some interesting mechanisms, but may not directly solve “the problem”

Disadvantages of Virtual Machines

- Feasibility issues
  - Hardware support? OS support?
  - Admin support?
  - Popularity of virtualization platforms argues these can be handled
- Performance issues
  - Is a 10-20% performance hit tolerable?
  - Can your NIC or disk keep up with the load?

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Full Virtualization

- **IBM CP-40 (1967)**
  - **Supported 14 simultaneous S/360 virtual machines**
- **Later evolved into CP/CMS and VM/CMS (still in use)**
  - **1,000 mainframe users, each with a private mainframe, running a text-based single-process "OS"**
- **Popek & Goldberg: Formal Requirements for Virtualizable Third Generation Architectures (1974)**
  - **Defines characteristics of a *Virtual Machine Monitor* (VMM)**
  - **Describes a set of architecture features sufficient to support virtualization**

Virtual Machine Monitor

- **Equivalence:**
  - Provides an environment essentially identical with the original machine
- **Efficiency:**
  - Programs running under a VMM should exhibit only minor decreases in speed
- **Resource Control:**
  - VMM is in complete control of system resources

Process : Kernel :: VM : VMM

Popek & Goldberg Instruction Classification

- ***Sensitive* instructions**:
  - **Attempt to change configuration of system resources**
    - **Disable interrupts**
    - **Change count-down timer value**
    - **...**
  - **Illustrate different behaviors depending on system configuration**
- ***Privileged* instructions**:
  - **Trap if the processor is in user mode**
  - **Do not trap if in supervisor mode**

Popek & Goldberg Theorem

"... a virtual machine monitor may be constructed if the set of sensitive instructions for that computer is a subset of the set of privileged instructions."

- All instructions must either:
  - Exhibit the same result in user and supervisor modes
  - Or, they must trap if executed in user mode
- Architectures that meet this requirement:
  - IBM S/370, Motorola 68010+, PowerPC, others.

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x86 Virtualization

- x86 ISA does not meet the Popek & Goldberg requirements for virtualization
- ISA contains 17+ sensitive, unprivileged instructions:
  - `SGDT, SIDT, SLDT, SMSW, PUSHF, POPF, LAR, LSL, VERR, VERW, POP, PUSH, CALL, JMP, INT, RET, STR, MOV`
  - Most simply reveal the processor's CPL
- Virtualization is still possible, requires a workaround

The “POPF Problem”

```
PUSHF                          # %EFLAGS onto stack
ANDL $0x003FFDFF, (%ESP)       # Clear IF on stack
POPF                           # Stack to %EFLAGS
```

- **If run in supervisor mode, interrupts are now off**
- **What “should” happen if this is run in user mode?**

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- **What “should” happen if this is run in user mode?**
  - **Attempting a privileged operation should trap**
  - **If it doesn't trap, the VMM can't simulate it**
    - **Because the VMM won't even know it happened**
- **What happens on the x86?**

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- **What happens on the x86?**
  - **CPU “helpfully” ignores changes to privileged bits when POPF run in user mode!**

VMware (1998)

- **Runs guest operating system in ring 3**
  - **Maintains the illusion of running the guest in ring 0**
- **Insensitive instruction sequences run by CPU at full speed:**
  - `movl 8(%ebp), %ecx`
  - `addl %ecx, %eax`
- **Privileged instructions trap to the VMM:**
  - `cli`
- **VMware performs *binary translation* on guest code to work around sensitive, unprivileged instructions:**
  - `popf` ⇒ `int $99`

VMware (1998)

Privileged instructions trap to the VMM:

```
cli
```

actually results in General Protection Fault (IDT entry #13), handled:

```
void gpf_exception(int vm_num, regs_t *regs)
{
    switch (vmm_get_faulting_opcode(regs->eip))
    {
        ...
        case CLI_OP:
            /* VM doesn't want interrupts now */
            vmm_defer_interrupts(vm_num);
            break;
        ...
    }
}
```

VMware (1998)

We wish `popf` trapped, but it doesn't.

Scan "code pages" of executable, translating

`popf` ⇒ `int $99`

which gets handled:

```
void popf_handler(int vm_num, regs_t *regs)
{
     regs->eflags = *(regs->esp);
     regs->esp++;
}
```

Related technologies

Software Fault Isolation (Lucco, UCB, 1993)

VX32 (Ford & Cox, MIT, 2008)

Virtual Memory

- We've virtualized instruction execution
  - How about other resources?
- Kernels access physical memory and implements virtual memory.
  - How do we virtualize physical memory?
    - Use virtual memory (obvious so far, isn’t it?)
  - If guest kernel runs in virtual memory, how does it provide virtual memory for processes?
    - VMM may have to “shadow” page-mapping tables
    - Set-CR3 traps, constructs *real* virtual memory
    - Writes to page directories and page tables are trapped, mapped to “shadow” tables

Hardware Assisted Virtualization

- Recent variants of the x86 ISA meet Popek & Goldberg requirements
  - Intel VT-x (2005), AMD-V (2006)
- VT-x introduces two new operating modes:
  - VMX root operation & VMX non-root operation
  - VMM runs in VMX root, guest OS runs in non-root
  - Both modes support all privilege rings
  - Guest OS runs in (non-root) ring 0, no illusions necessary
- At least initially, binary translation faster than VT
  - `int $99` is a “regular” trap, faster than a “special trap”

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Paravirtualization (Denali 2002, Xen 2003)

- Motivation
  - Binary translation and shadow page tables are hard
- First observation:
  - *If* OS is open, it can be modified at the source level to make virtualization explicit (not transparent), and easier
- Paravirtualizing VMMs (hypervisors) virtualize only a subset of the x86 execution environment
- Run guest OS in rings 1-3
  - No illusion about running in a virtual environment
  - Guests may not use sensitive, unprivileged instructions and expect a privileged result
- Requires source modification only to guest kernels
  - Abstracting page-tables is a big win
- No modifications to user-level code and applications

Paravirtualization (Denali 2002, Xen 2003)

- **Second observation:**
  - **Regular VMMs must emulate hardware for devices**
    - **Disk, Ethernet, etc**
    - **Performance is poor due to constrained device API**
      - **To "send packet", must emulate many device-register accesses (inb/outb or MMIO, interrupt enable/disable)**
      - **Each step results in a trap**
  - **Already modifying guest kernel, why not provide virtual device drivers?**
    - **Virtual Ethernet could export send_packet(addr, len)**
      - **This requires only one trap**
- **"Hypercall" interface:**

syscall : kernel :: hypercall : hypervisor

VMware vs. Paravirtualization

- Kernel's device communication with VMware (emulated):

```
void nic_write_buffer(char *buf, int size)
{
    for (; size > 0; size--) {
        nic_poll_ready();
        outb(NIC_TX_BUF, *buf++);
    }
}
```

- Kernel's device communication with hypervisor (hypercall):

```
void nic_write_buffer(char *buf, int size)
{
    vmm_write(NIC_TX_BUF, buf, size);
}
```

Xen (2003)

- Popular hypervisor supporting paravirtualization
  - Hypervisor runs on hardware
  - Runs two kinds of kernels
  - Host kernel runs in domain 0 (dom0)
    - Required by Xen to boot
    - Hypervisor contains no peripheral device drivers
    - dom0 needed to communicate with devices
    - Supports all peripherals that Linux or NetBSD do!
  - Guest kernels run in unprivileged domains (domU's)

Xen (2003)

- Provides virtual devices to guest kernels
  - Virtual block device, virtual ethernet device
  - Devices communicate with hypercalls & ring buffers
  - Can also assign PCI devices to specific domUs
    - Video card
- Also supports hardware assisted virtualization (HVM)
  - Allows Xen to run unmodified domU's
  - Useful for bootstrapping
  - Also used for “the OS” that can't be source modified
- Supports Linux & NetBSD as dom0 kernels
- Linux, FreeBSD, NetBSD, and Solaris as domU's

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chroot()

- Venerable Unix system call
- Runs a Unix process with a different root directory
  - Almost like having a separate file system
- Share the same kernel & non-filesystem “things”
  - Networking, process control
- Only a minimal sandbox.
  - /proc, /sys
  - Resources: I/O bandwidth, cpu time, memory, disk space, …

User-mode Linux

- Runs a guest Linux kernel as a user space process under a regular Linux kernel
- Requires highly modified Linux kernel
- No modification to application code
- Used to be popular among hosting providers
- More mature than Xen, roughly equivalent, but much slower because Xen is designed to host kernels

Container-based OS Virtualization

- **Allows multiple instances of an OS to run in isolated *containers* under the same kernel**
- **Assumptions:**
  - **Want strong separation between “virtual machines”**
  - **But we can trust the kernel**
  - **Every “virtual machine” can use the same kernel version**
- **It follows that:**
  - **Don’t need to virtualize the kernel**
  - **Instead, beef up naming and partitioning inside the kernel: Each *container* can have:**
    - **User id, pid, tid space**
    - **Domain name**
    - **Isolated file system, OS version, libraries, etc.**
- **Total isolation between containers without virtualization overhead.**
- **VServer, FBSD Jails, OpenVZ, Solaris Containers (aka “Zones”)**

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Full System Simulation (Simics 1998)

- Software simulates hardware components that make up a target machine
- Interpreter executes each instruction & updates the software representation of the hardware state
- Approach is very accurate but very slow
- Great for OS development & debugging
- Break on triple fault is better than a reset

System Emulation (Bochs, DOSBox, QEMU)

- Seeks to emulate just enough of system hardware components to create an accurate "user experience"
- Typically CPU & memory subsystems are emulated
  - Buses are not
  - Devices communicate with CPU & memory directly
- Many shortcuts taken to achieve better performance
  - Reduces overall system accuracy
  - Code designed to run correctly on real hardware executes "pretty well"
  - Code not designed to run correctly on real hardware exhibits wildly divergent behavior
- E.g. run legacy 680x0 code on PowerPC, run Windows on ??

System Emulation Techniques

- **Pure interpretation:**
  - Interpret each guest instruction
  - Perform a semantically equivalent operation on host
- **Static translation:**
  - Translate each guest instruction to host once
  - Happens at startup
  - Limited applicability, no self-modifying code

System Emulation Techniques

- **Dynamic translation:**
  - Translate a block of guest instructions to host instructions just prior to execution of that block
  - Cache translated blocks for better performance
- **Dynamic recompilation & adaptive optimization:**
  - Discover what algorithm the guest code implements
  - Substitute with an optimized version on the host
  - Hard

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Are We Having Fun Yet?

- **Virtualization is great if you need it**
  - **If you must have 35 /etc/passwd's, 35 sets of users, 35 Ethernet cards, etc.**
  - **There are many techniques, which work (are secure and fast enough)**
- **Virtualization is overkill if we need only isolation**
  - **Remember the Java "virtual machine"??**
    - **Secure isolation for multiple applications**
    - **Old approach – Smalltalk (1980)**
    - **New approach – Google App Engine**
- **Open question**
  - **How *best* to get isolation, machine independence?**

Summary

- Virtualization is big in enterprise hosting
- {Full, hardware assisted, para-}virtualization
- Containers: VM-like abstraction with high efficiency
- Emulation is a slower alternative, more flexibility

Further Reading

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