Virtualization

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Outline

- Introduction
  - What, why?
- Basic techniques
  - Simulation
  - Binary translation
- Kinds of instructions
- Virtualization
  - x86 Virtualization
  - Paravirtualization
- Summary

What is Virtualization?

- **Virtualization:**
  - **Practice 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**

Process vs. Virtualization

- **The *Process abstraction* is a “weak, fuzzy” form of virtualization**
  - **Many process resources exactly match machine resources**
    - **%eax, %ebx, …**
  - **Some machine resources are not visible to processes**
    - **%cr0**
  - **Some process resources are “inspired by” hardware**
    - **SIGALARM**
  - **Some process resources are “invented” - don't match any hardware feature**
    - **“current directory” and “umask”**
- **Virtualization is “more like hardware” than processes**
  - **What runs inside virtualization is an operating system**

Process : Kernel :: Kernel : ?

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Process : Kernel :: Kernel : Virtual-machine monitor

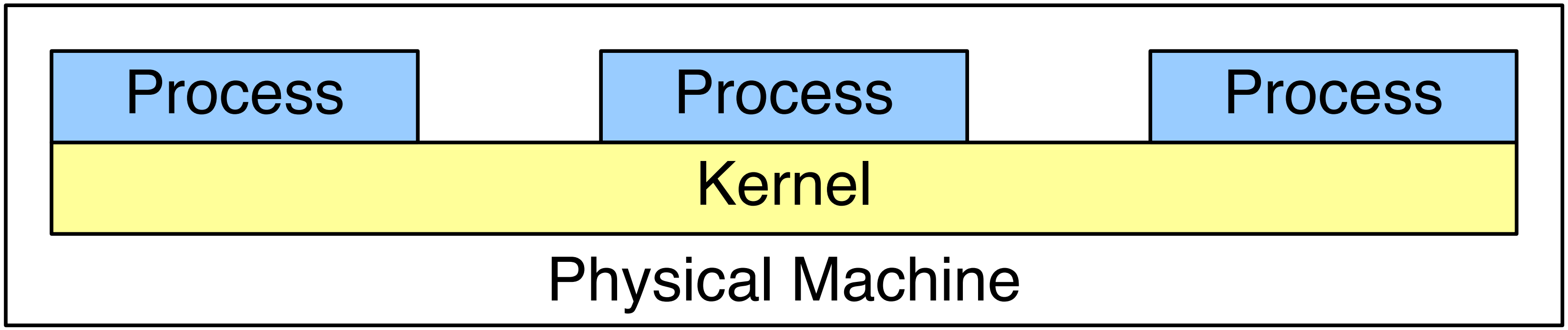
Advantages of the Process Abstraction

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

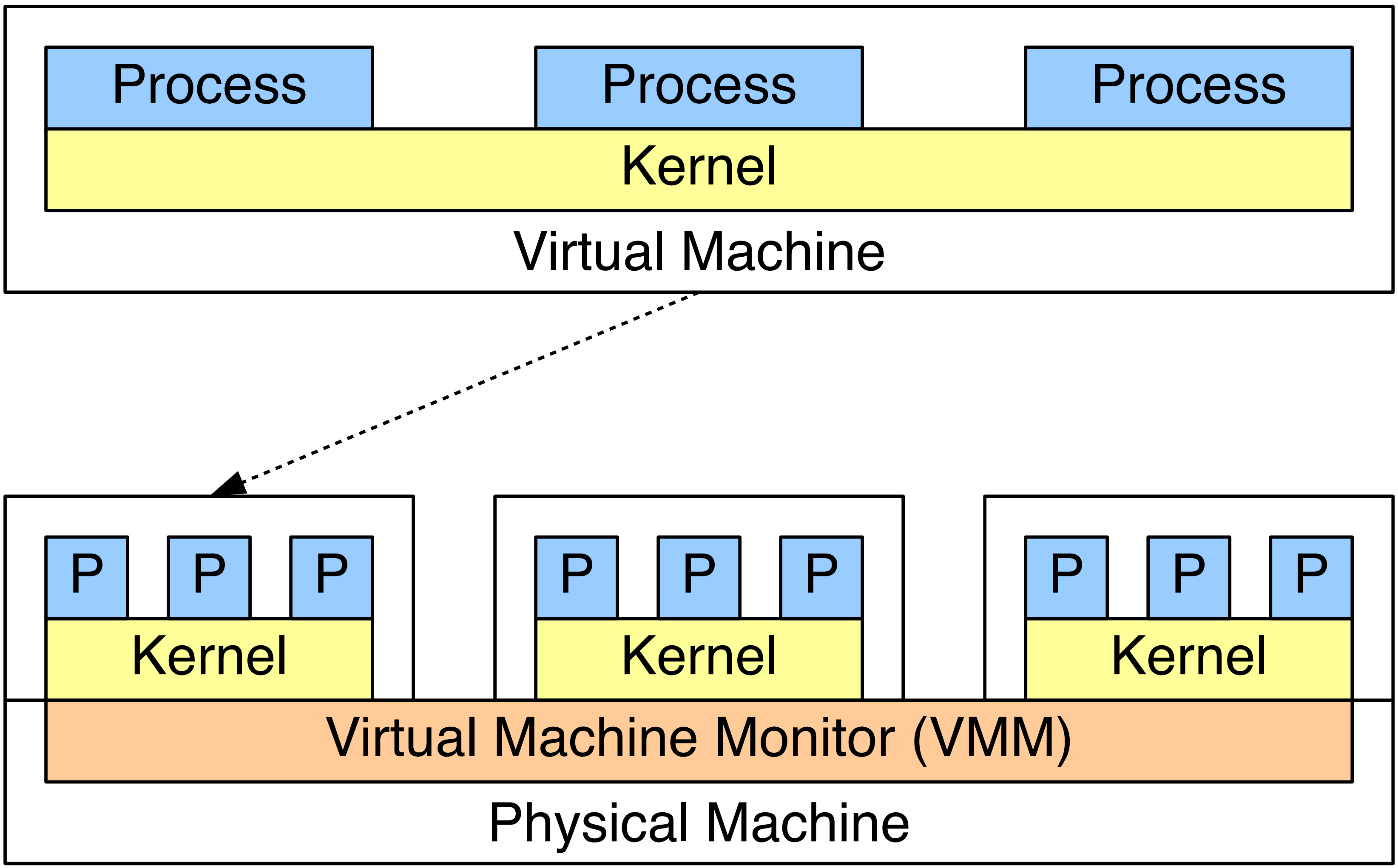
Disadvantages of the Process Abstraction

- 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
- Processes share the same kernel
  - Kernels are *huge*, lots of possibly-buggy code
- Processes have limited degree of protection, even from each other
  - Linux “OOM killer” can kill one process if another uses lots of memory
- Overall, processes aren't *that* isolated from each other...

Process/Kernel Stack



Virtualization Stack



Why Use Virtualization?

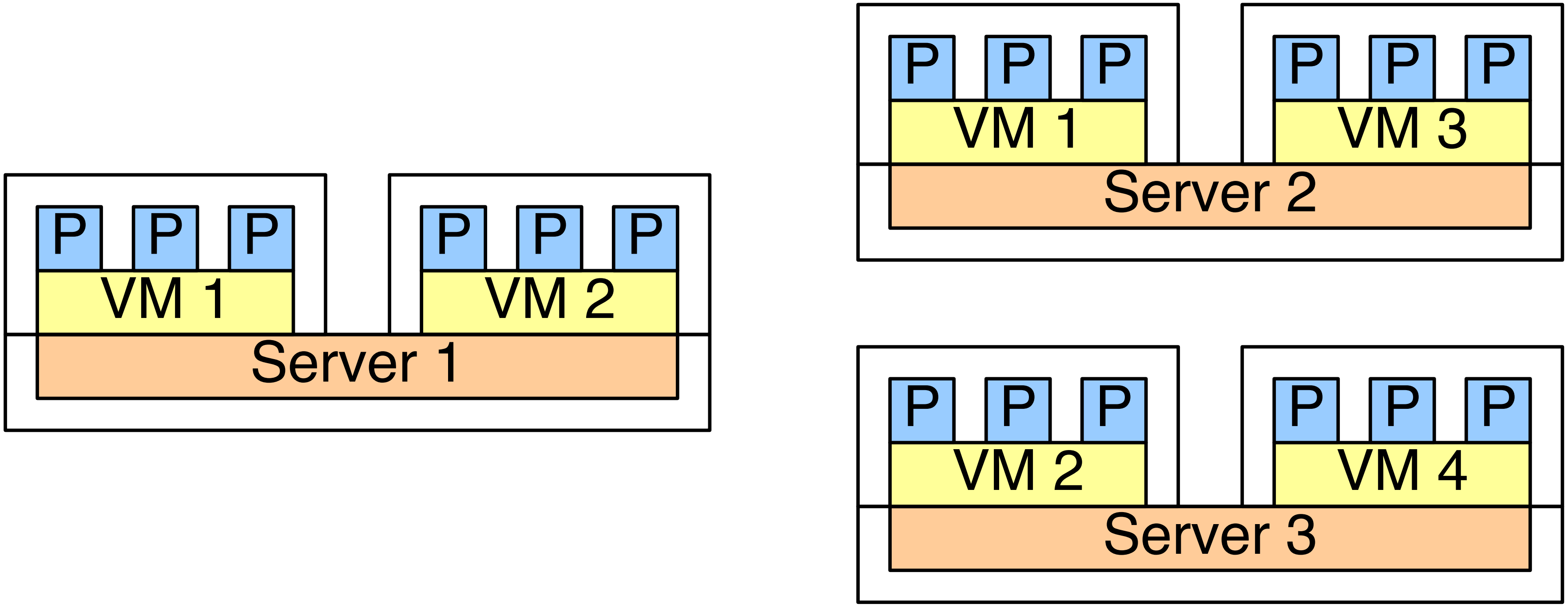
- Run two operating systems on the same machine!
  - "Windows+Linux" was VMware's first business model
  - Hobbyists like to run ancient-history OS's
- Debugging OS's is more pleasant
  - Also: instrumenting what an OS does
  - *Monitoring a captive OS for security infestations*
- "Process abstraction" at the *kernel* layer
  - Separate file system
  - Multiple machine owners
  - Better protection than one kernel's processes (in theory)
    - "Small, secure" hypervisor, "small, fair" scheduler

Why Use Virtualization?

- *Huge* impact on enterprise hosting
  - No longer need to sell whole machines
  - Sell machine *slices*
    - “xx GB RAM, yy cores” - smoother than “n Dell PowerEdge 2600's”
    - 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
    - Deal with machine failures or machine-room flooding
  - VM replication to provide fault tolerance
    - “Why bother doing it at the application level?”
- Can overcommit hardware
  - Most VM's are not 100% busy all the time
  - If one suddenly becomes 100% busy, move it to a dedicated machine for a few hours, then move it back

Virtualization in Enterprise

- **Separates product (OS services) from physical resources (server hardware)**
- **Live migration example:**



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?
    - When an IPC becomes an RPC the cost goes up dramatically
  - Can your NIC or disk keep up with the load of multiple virtual machines?
  - Interdomain DoS? Thrashing?
- “Nothing fails like success”
  - VMMs are getting larger, and potentially home to security bugs

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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 real hardware suddenly rebooting
  - Possible to debug a driver for a hardware device that hasn't been built yet

System Emulation (Bochs, DOSBox, QEMU, fake86)

- Emulate just enough of hardware components to create an accurate "user experience"
- Typically CPU & memory are emulated
  - Buses are not
  - Devices communicate with CPU & memory directly
- Shortcuts are 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

System Emulation Techniques

- **Pure interpretation:**
  - Interpret each guest instruction
  - Perform a semantically equivalent operation on host
- **Static translation:**
  - Translate each guest instruction to host instructions *once*
  - Example: DEC "mx" translator
    - Input: MIPS Ultrix executable
    - Output: Alpha OSF/1 executable
  - Limited applicability; self-modifying code doesn't work

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
  - Like a Smalltalk/Java "JIT"
- Dynamic recompilation & adaptive optimization:
  - Discover which algorithm the guest code implements
  - Substitute with an optimized version on the host
  - Hard

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Kinds of Instructions

- “Regular”
  - ADD, XOR
  - Load, store
  - Branch, push, pop
- “Special”
  - CLI/STI, HLT, read/modify %cr3
- Devices (magic side-effects)
  - INB/OUTB
  - Stores into video RAM!
- How do we emulate?
  - “Regular”, “Special” - just simulate the CPU
  - Devices – *very* difficult!
    - *Thousands* of devices exist, each one is extremely complex
    - A device emulator may be 100 lines of code, or 10,000

The Need for Speed

- “Slow” is easy
  - Simulation is naturally slow
  - Binary translation requires lots of “compilation”
- Key observation
  - “Run virtual X on physical X” should be faster than “run virtual X on physical Y”
  - “x86 on x86” should be faster than “x86 on PowerPC”
  - We don't need to *simulate* hardware if we can *use* it
    - “The best simulation of REP STOSB is REP STOSB”
- while(1)
  - Find a big block of “regular” instructions
  - Load up register values, jump to start of block
    - These instructions run at full speed
  - When something goes wrong, figure out a fix
    - This part is slow

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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 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."

- Each instruction must either:
  - Exhibit the same result in user and supervisor modes
  - Else trap if executed in user mode
- Then a VMM can ***run a guest kernel in user mode!***
  - Sensitive instructions are trapped, handled by VMM
- Architectures that meet this requirement:
  - IBM S/370, Motorola 68010+, PowerPC, others.

x86 Virtualization

- x86 ISA (pre-2005) 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 that the “kernel” is running in user mode
    - PUSHF
    - PUSH %CS
  - Some *execute inaccurately*
    - POPF
- Virtualization is still possible, requires workarounds

The “POPF Problem”

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

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

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- **If run in supervisor mode, interrupts are now off**
- **What “should” happen if this is run in user mode?**
  - **Attempting a privileged operation should trap to VMM**
  - **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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    - Because the VMM won't even know it happened
- What happens on the x86?
  - CPU “helpfully” *ignores changes to privileged bits* when POPF runs in user mode!
  - So that sequence does *nothing*, no trap, VMM can't simulate

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`
- ***Sensitive, unprivileged* instructions handled by *binary translation*:**
  - `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 OP_CLI:
            /* 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) {
    unsigned int oldef = regs->eflags;
    unsigned int newef = *(regs->esp);
    if (!vm->pl0 && (newef & EFLAGS_SENSITIVE))
        gpf_handler(...);
    regs->eflags = newef;
    regs->esp++;
    if (!(oldef&EFLAGS_IF) && (newef&EFLAGS_IF)
        deliver_pending_interrupts(vm);
    ...
}
```

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 use physical memory to implement virtual memory
  - How do we virtualize physical memory?
    - Each guest kernel must be protected from the others, so we can't let them access physical memory
    - Ok, use virtual memory (obvious so far, isn’t it?)

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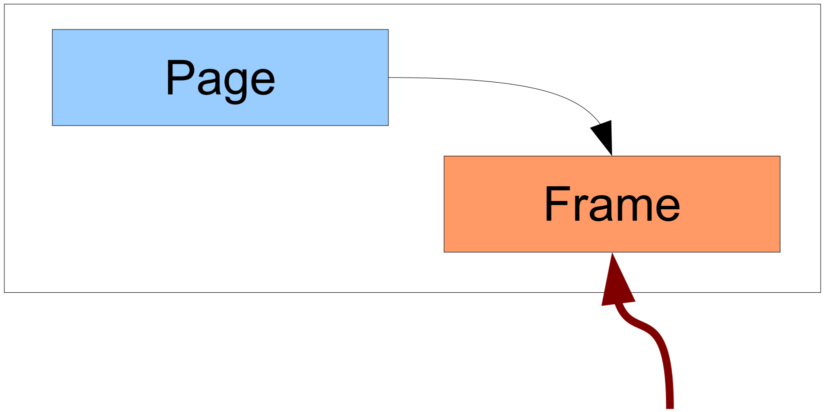
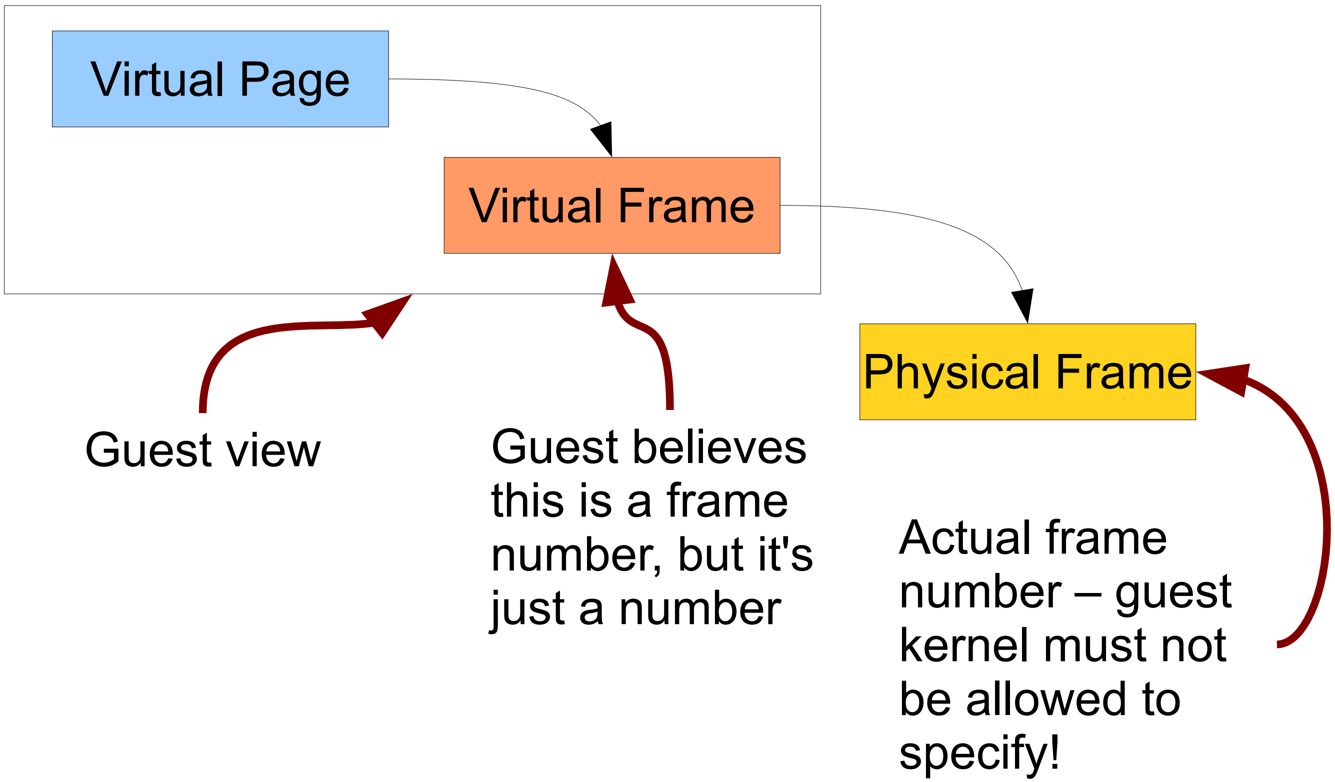
    - Each guest kernel must be protected from the others, so we can't let them access physical memory
    - Ok, use virtual memory (obvious so far, isn’t it?)
  - But guest kernels themselves provide virtual memory to their processes
    - They like to “MOVL %EAX, %CR3”
    - We can't allow them to do that!
    - Can we simulate it??

VM – Guest-kernel view

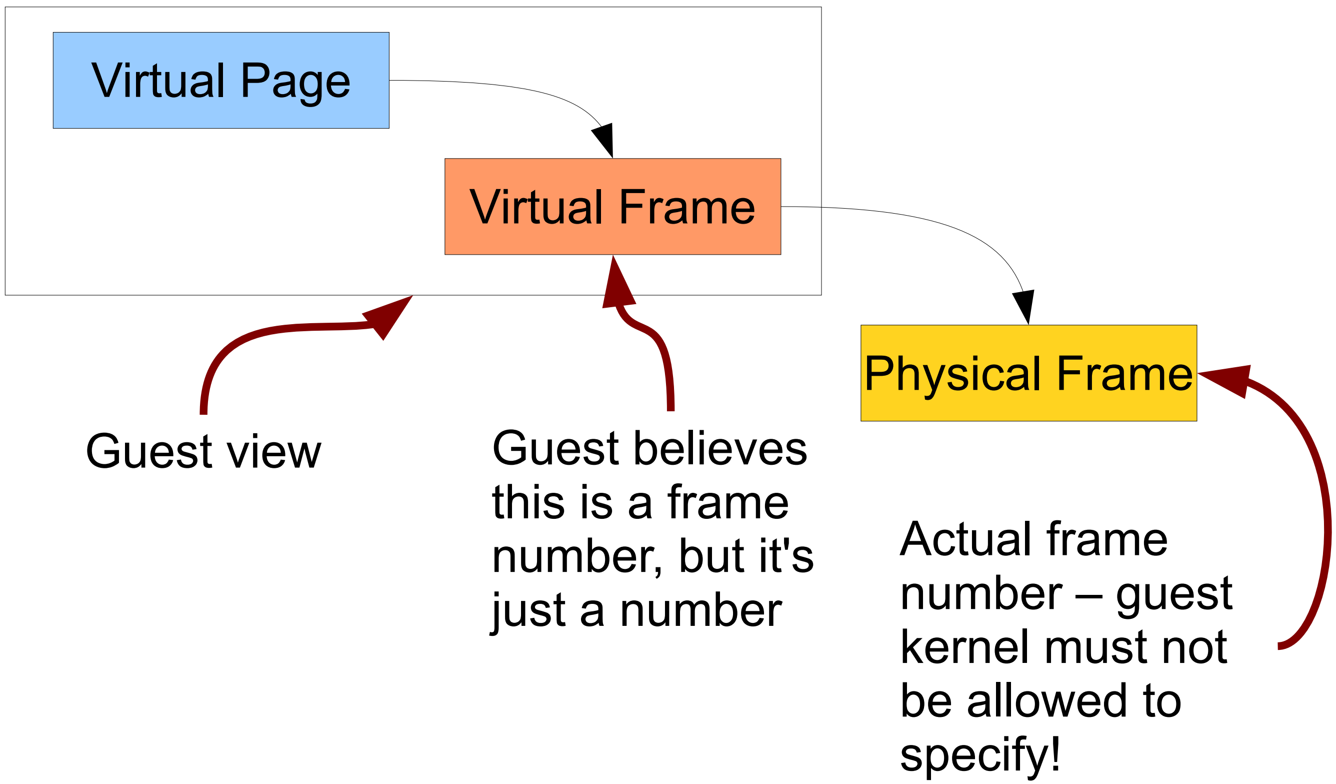


Guest believes
its RAM has
frames 0..N

VM – Fiction vs. Reality

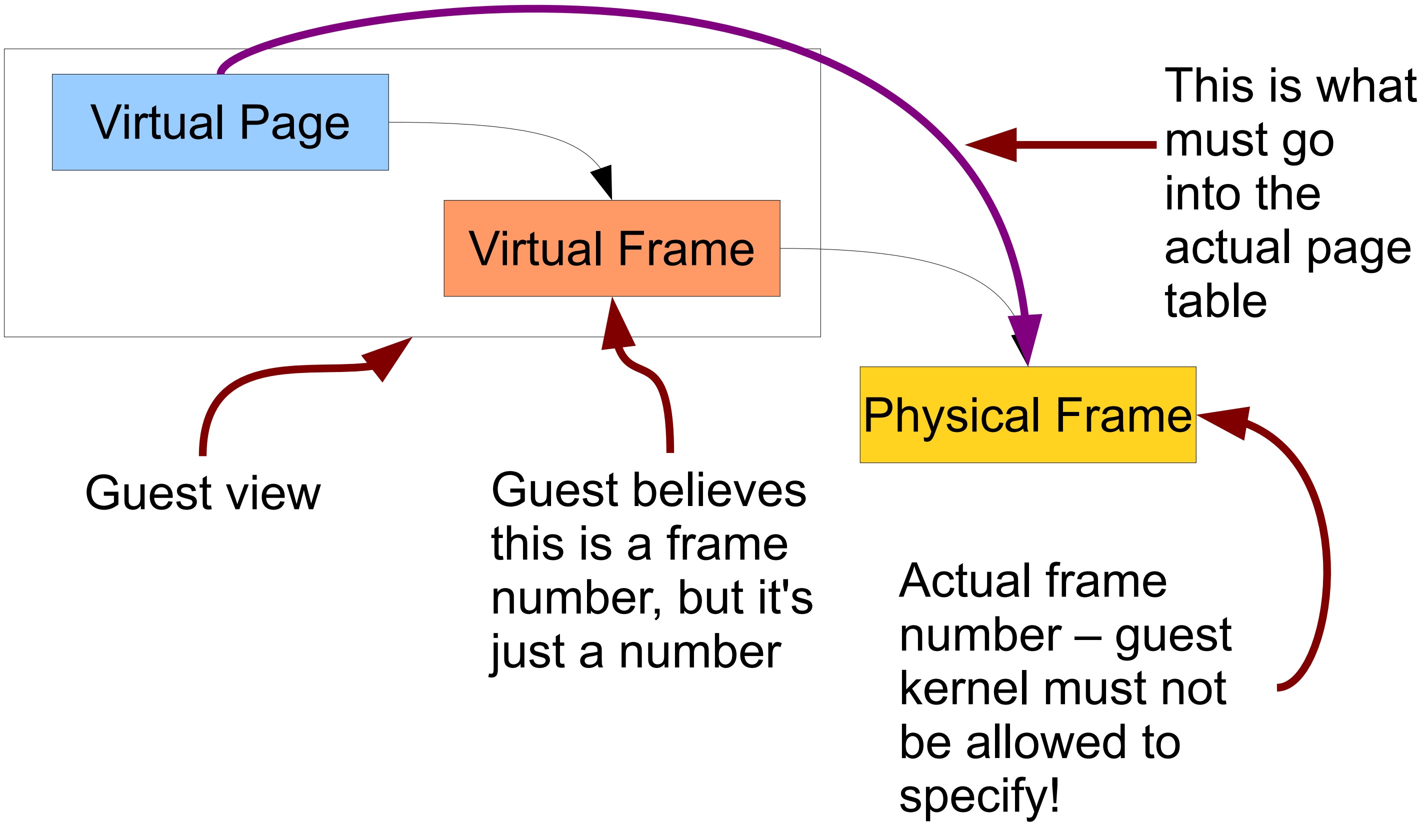


VM – How to do it?

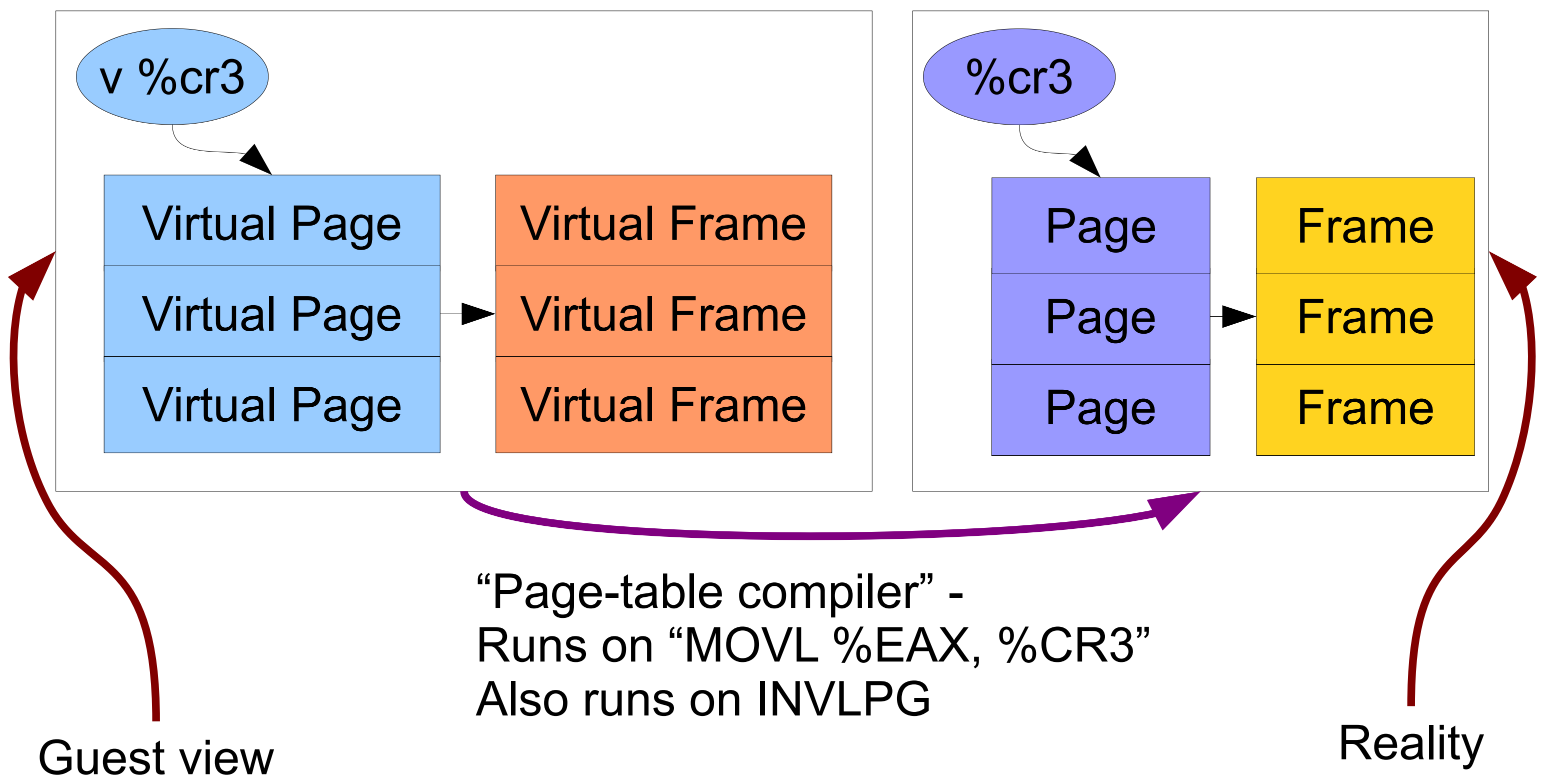


Note: traditional x86 VM hardware does not implement “map, then map again’

VM – How to do it?



VM – Shadow Page Tables



Shadow Page Tables

- Accesses to %cr3 are trapped by hardware
  - Store into %cr3?
    - "Compile" guest-kernel page table into real page table
      - Map guest frame numbers into actual frame numbers
    - Secretly set %cr3 to point to real page table
  - Fetch from %cr3?
    - Return the guest-kernel "physical" address of the virtual page table in guest-kernel virtual memory, not the physical address of the actual page table in physical memory

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  - But if guest *stores* into a fake PTE, we must re-compile
  - So virtual page tables are read-only pages for the guest

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  - So virtual page tables are read-only pages for the guest
- Guest kernel sets some pages to "kernel only"
  - Each guest page table compiles to *two* real page tables
    - guest-kernel-mode has all pages, guest-user-mode doesn't

Wow, This is Hard!

- Many tricks played to improve performance
  - Compiling page-tables is slow, so cache old compilations
  - When to garbage-collect them?
- PTE's contain dirty & accessed bits
  - Won't cover that today
- Guest kernel may be able to tell it is running in a VM
  - Some sensitive instructions may leak user-mode-ness
  - Virtual devices may behave subtly wrong
  - Time dilation may be observed

- Is there an easier way??

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- Is there an easier way??
  1. Fix the hardware
  2. Blur the hardware ("paravirtualization")

Hardware Assisted Virtualization

- Modern x86's *do* 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
    - VMM tells hardware "Enter guest mode, but trap on these conditions: ..."
    - If guest kernel runs a sensitive instruction, hardware does a "VM exit" back to VMM, indicates why
- 2^{nd}-generation VT-x has "EPT": hardware fix for VM
  - Host sets up page tables giving "virtual physical pages" to guest
  - Guest page tables map "virtual virtual pages" to them

Paravirtualization (Denali 2002, Xen 2003)

- Motivation
  - Binary translation and shadow page tables are hard
- First observation:
  - If OS is open-source, it can be modified at the source level to make virtualization explicit (not transparent), and easier
    - Replace “MOVL %EAX, %CR3” with “install_page_table()”
    - Typically only a small fraction of the guest kernel needs to be edited
    - Guest *user* code is not changed at all
- 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

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();           // many traps
        outb(NIC_TX_BUF, *buf++);   // many traps
    }
}
```

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

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

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 porting an OS to Xen PV
  - Also used for “certain OSes” with closed source
- Supports Linux & NetBSD as dom0 kernels
- Linux, FreeBSD, NetBSD, and Solaris as domU's

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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, Heroku, etc.**
- **Open question**
  - **How *best* to get isolation, machine independence?**

Summary

- What virtualization does
  - Multiple OS's on one laptop
  - Debugging, security analysis
  - Enterprise
    - Efficiency
    - Reliability (outage resistance)
- The problem
  - Kinds of instructions
- Solutions
  - Binary translation (useful for light-weight uses)
  - {Full, hardware assisted, para-}virtualization
- Many things not covered today!
  - “I/O virtualization” - attaching real devices to virtual machines
  - ...

Further Reading

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