Machine Virtualization for Fun, Profit, and Security

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Background: x86 machine virtualization

- Running multiple different unmodified operating systems
- Each in an isolated virtual machine
- Simultaneously
- On the x86 architecture
- Many uses: live migration, record & replay, testing, . . . , security
- Foundation of IaaS cloud computing
- Used nearly everywhere

x86 virtualization primer

- What is the problem?
- Popek and Goldberg's virtualization model [Popek74]: Trap and emulate
- Privileged instructions trap to the hypervisor
- Hypervisor emulates their behavior
- Without hardware support
- With hardware support

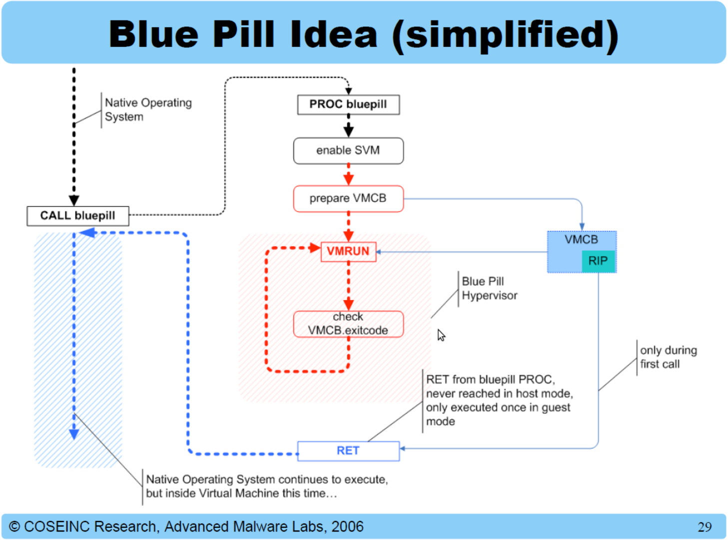
What is a rootkit?

- First you take control. How?
- Then you hide to avoid detection and maintain control. How?
- Usual methods are ugly and intrusive: easy to detect!
- Can we do better?

Hypervisor-level rootkits

- Hypervisors have full control over the hardware
- Hypervisors can trap any operating system event
- Code can enter hypervisor-mode at any time
- Solution: run the rootkit as a hypervisor

Bluepill: a hypervisor level rootkit [Rutkowska06]



Bluepill cont'

- Bluepill installs itself on the fly
- Can you bluepill bluepill?

What is the Turtles project?

- Efficient nested virtualization for Intel x86 based on KVM
- Runs multiple guest hypervisors and VMs: KVM, VMware, Linux, Windows, . . .
- Code publicly available

What is the Turtles project? (cont')

- Nested VMX virtualization for nested CPU virtualization
- Multi-dimensional paging for nested MMU virtualization
- Multi-level device assignment for nested I/O virtualization
- Micro-optimizations to make it go fast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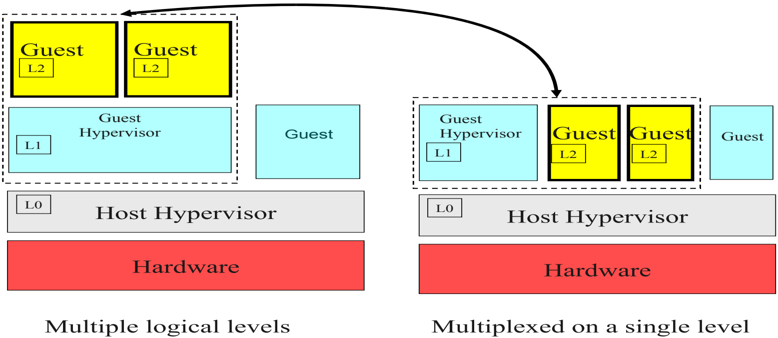
Theory of nested CPU virtualization

- Trap and emulate[PopekGoldberg74] ⇒ it's all about the traps
- Single-level (x86) vs. multi-level (e.g., z/VM)
- Single level ⇒ one hypervisor, many guests
- Turtles approach: L_0 multiplexes the hardware between L_1 and L_2, running both as guests of L_0—without either being aware of it
- (Scheme generalized for n levels; Our focus is n=2)



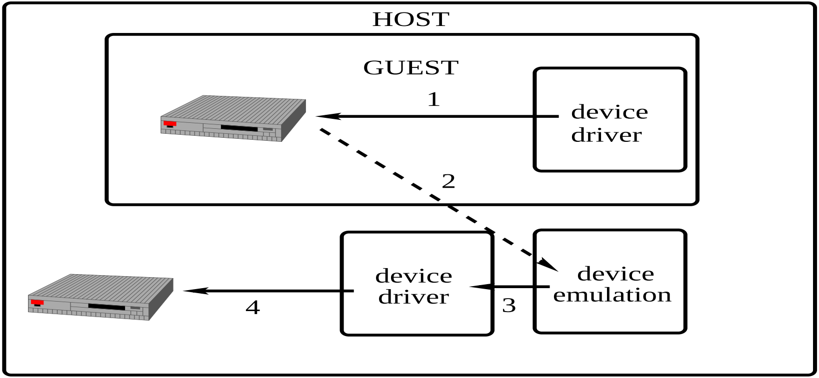
Detecting hypervisor-based rootkits

- Bluepill authors claim “undetectable”
- “Compatibility is Not Transparency: VMM Detection Myths and Realities” [Garfinkel07]
- Hardware discrepancies
- Resource-sharing attacks
- Timing attacks: PCI register access, page-faults on MMIO access, cpuid timing vs. nops
- Can you trust time?

What does it mean, to do I/O?

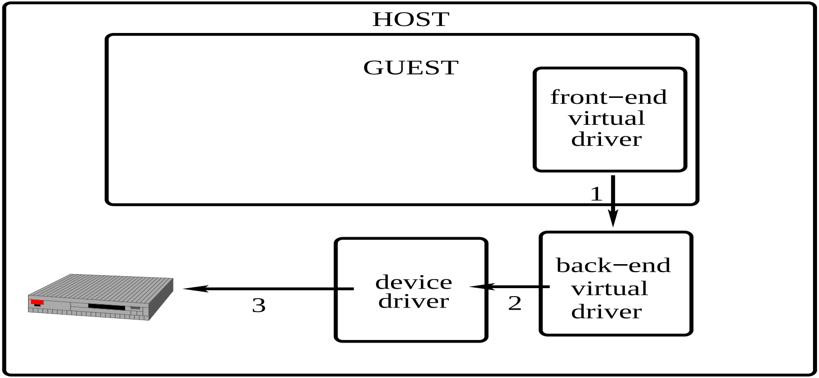
- Programmed I/O (in/out instructions)
- Memory-mapped I/O (loads and stores)
- Direct memory access (DMA)
- Interrupts

I/O virtualization via device emulation



- Emulation is usually the default [Sugerman01]
- Works for unmodified guests out of the box
- Very low performance, due to many exits on the I/O path

I/O virtualization via paravirtualized devices

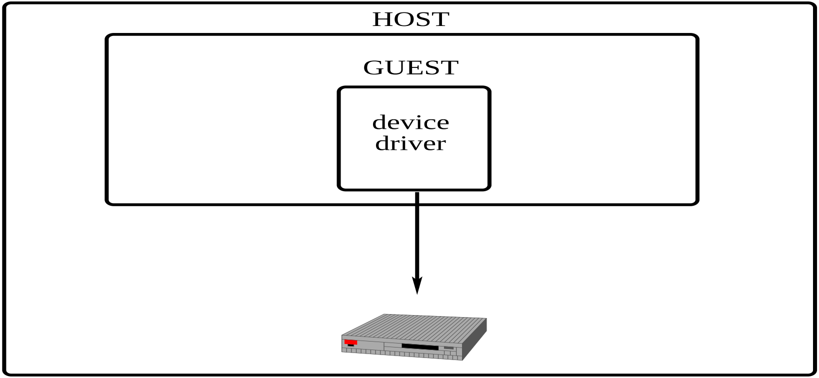


- Hypervisor aware drivers and “devices” [Barham03,Russell08]
- Requires new guest drivers
- Requires hypervisor involvement on the I/O path

Hypervisor-based I/O introspection

- Useful: anti-virus, intrustion detection, compression, live migration, . . .
- Q1: how do you do it without impacting performance?
- Q2: how do you bridge the semantic gap?

I/O virtualization via device assignment



- Bypass the hypervisor on I/O path [Levasseur04,Ben-Yehuda06]
- SR-IOV devices provide sharing in hardware
- Best performance: 100% of bare-metal! [Gordon12]

Comparing I/O virtualization methods

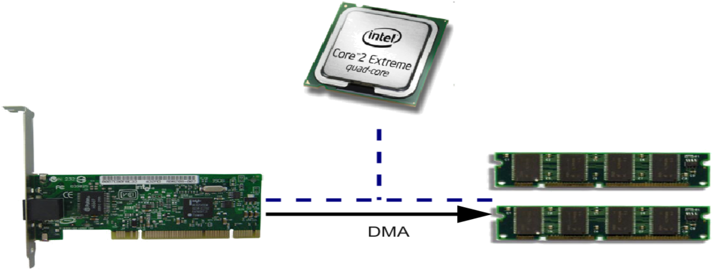
IOV method	throughput (Mb/s)	CPU utilization
bare-metal	950	20%
device assignment	950	25%
paravirtual	950	50%
emulation	250	100%

- `netperf` TCP_STREAM sender on 1Gb/s Ethernet (16K msgs)
- Device assignment best performing option
- Challenges: DMA and interrupts

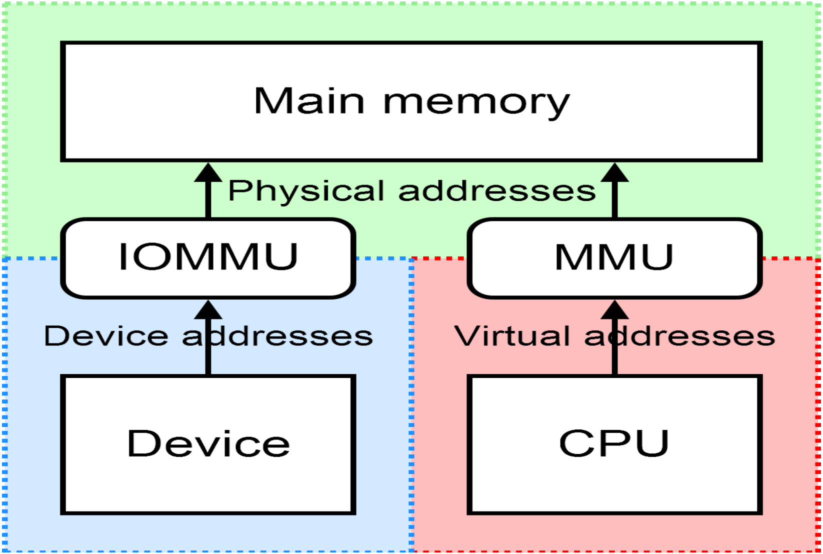
Table from "The Turtles Project: Design and Implementation of Nested Virtualization" [Ben-Yehuda10]

Direct memory access (DMA)

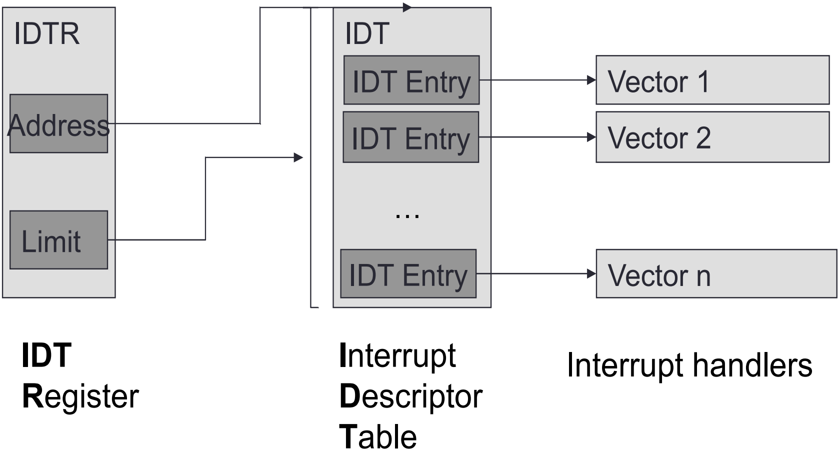
- All modern devices access memory directly
- On bare-metal:
  - A trusted driver gives its device an address
  - Device reads or writes that address
- Protection problem: guest drivers are not trusted
- Translation problem: guest memory $\neq$ host memory
- Direct access: the guest bypasses the host
- What is the obvious attack?
- How do you protect against it?



IOMMU


Main memory
Physical addresses
IOMMU
MMU
Device addresses
Virtual addresses
Device
CPU

Background: interrupts

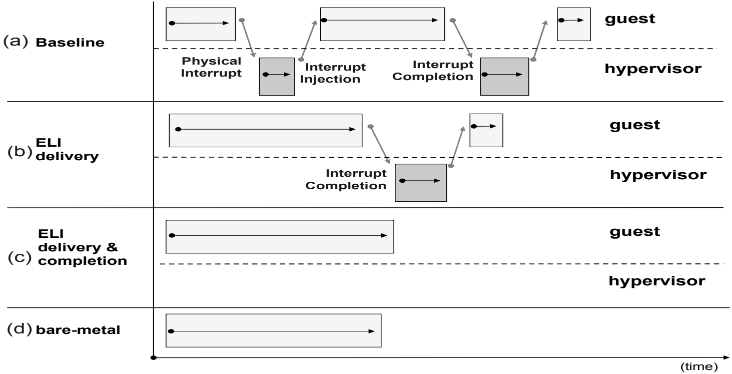


- I/O devices raise interrupts
- CPU temporarily stops the currently executing code
- CPU jumps to a pre-specified interrupt handler

Interrupt-based attacks

- Follow the White Rabbit [Rutkowska11]
- Tell the device to generate “interesting” interrupts
- Attack: fool the CPU into SIPI
- Attack: syscall/hypercall injection
- Interrupt-based attacks: guest generating interrupts which are handled in host mode
- Why not handle interrupts in guest mode?

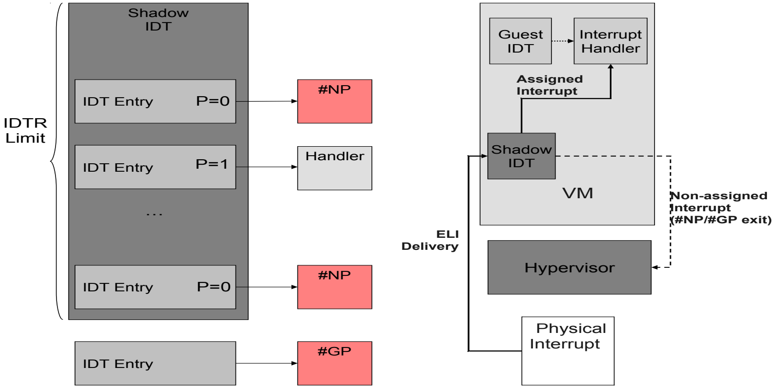
ELI: Exitless Interrupts



ELI: direct interrupts for unmodified, untrusted guests

"ELI: Bare-Metal Performance for I/O Virtualization", Gordon, Amit, Hare'El, Ben-Yehuda, Landau, Schuster, Tsafrir, ASPLOS '12

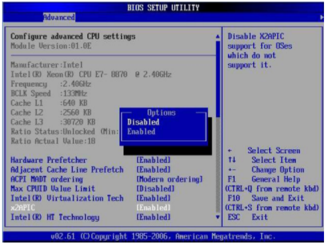
ELI: delivery



- All interrupts are delivered directly to the guest
- Host and other guests' interrupts are bounced back to the host
- ...without the guest being aware of it

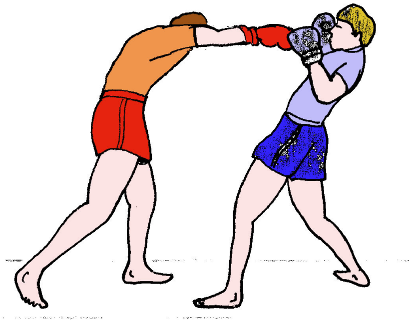
ELI: signaling completion

- Guests signal interrupt completions by writing to the Local Advance Programmable Interrupt Controller (LAPIC) End-of-Interrupt (EOI) register
- Old LAPIC: hypervisor traps load/stores to LAPIC page
- x2APIC: hypervisor can trap specific registers



- Signaling completion without trapping requires x2APIC
- ELI gives the guest direct access only to the EOI register

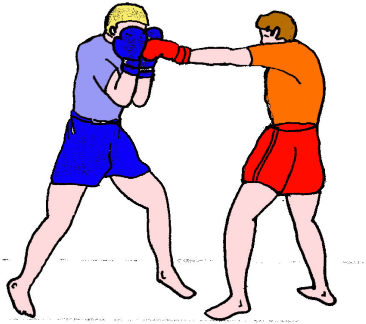
ELI: threat model



Threats: malicious guests might try to:

- keep interrupts disabled
- signal invalid completions
- consume other guests or host interrupts

ELI: protection



- VMX preemption timer to force exits instead of timer interrupts
- Ignore spurious EOIs
- Protect critical interrupts by:
  - Delivering them to a non-ELI core if available
  - Redirecting them as NMIs→unconditional exit
  - Use IDTR limit to force #GP exits on critical interrupts

Conclusions

- Machine virtualizaion is very useful
- Can be used for good, or evil
- Complexity leads to unintended consequences
- Happy hacking!