CS 134
Operating Systems

April 24, 2019

Virtualization II

Based on Virtualization

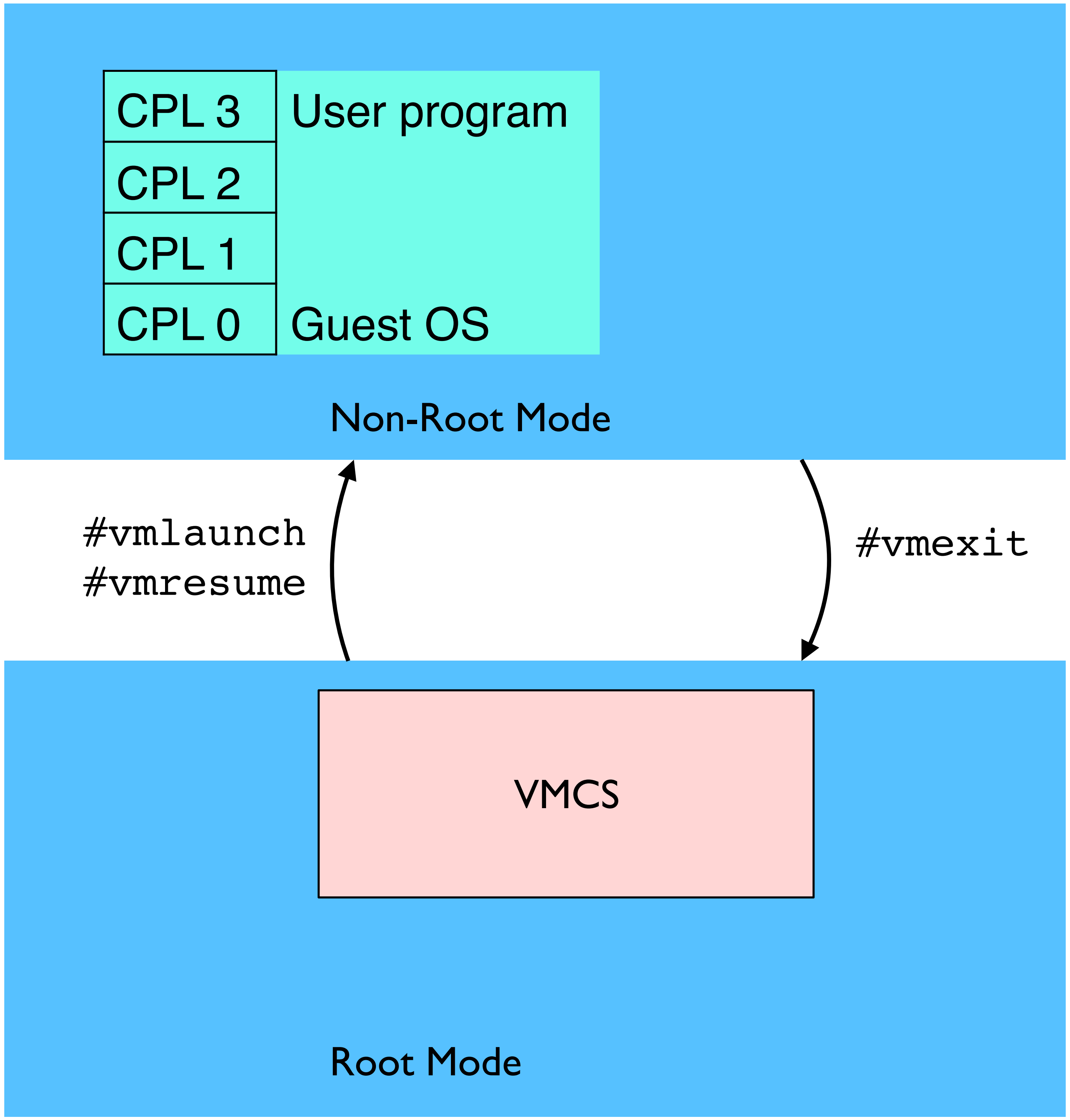
Outline

- Last lecture: basics of virtualization
  - VMM is an OS that maintains a machine-like interface instead of a process interface
  - Many reasons to use virtualization
  - Originally, virtualization wasn't thought possible on x86
  - VMware introduced binary translation
- This lecture: recent developments
  - More detailed discussion of HW support for virtualization
  - Safe user-level access to privileged CPU features

Intel VT-x

- Makes x86 hardware “classically virtualizable” (as defined by Popek and Goldberg)
- Goal: **Direct execution** of most privileged instructions
- Introduces two CPU modes:
  - VMX root mode: for running VMM
  - VMX non-root mode: for running VMs (guest)
  - Each mode has its own rings (CPL0-CPL3)
- In-memory structure called VM Control Structure (VMCS) stores privileged register state and control flags

Intel VT-x

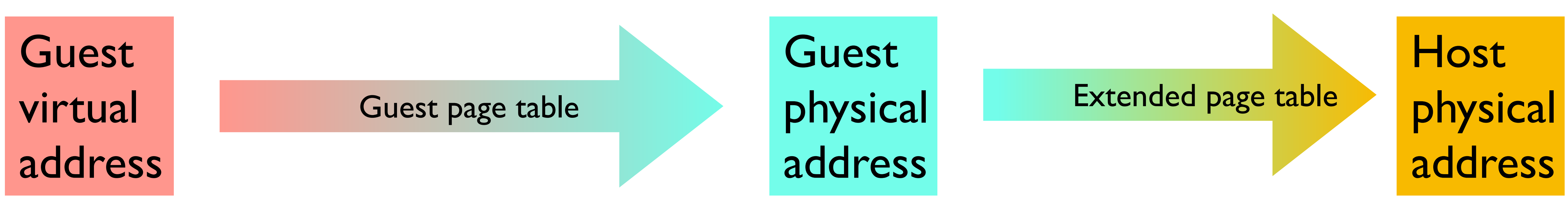

CPL 3
User program
CPL 2
CPL 1
CPL 0
Guest OS
Non-Root Mode
#vmlaunch
#vmresume
#vmexit
VMCS
Root Mode

VM enter and VM exit

- Transitions between VMX root mode and VMX non-root mode
- VM Exit
  - `vmcall` instruction
  - EPT page faults
  - Some trap-and-emulate (configured in VMCS)
  - Interrupts
- VM Enter
  - `vmlaunch` instruction: Enter VMX non-root mode for a new VMCS
  - `vmresume` instruction: Enter for the last VMCS
- Typical vmexit/vmenter is ~200 cycles on modern HW

Intel Extended Page Tables (EPT)

- Goal: Direct execution of guest page-table interactions
  - Reads and writes to page table in memory
  - `mov %eax, %cr3`
  - `invlpg`, etc.
- Idea: maintain two layers of paging translation
  - Normal page-table: Guest-virtual to guest-physical
  - EPT: guest-physical to host-physical

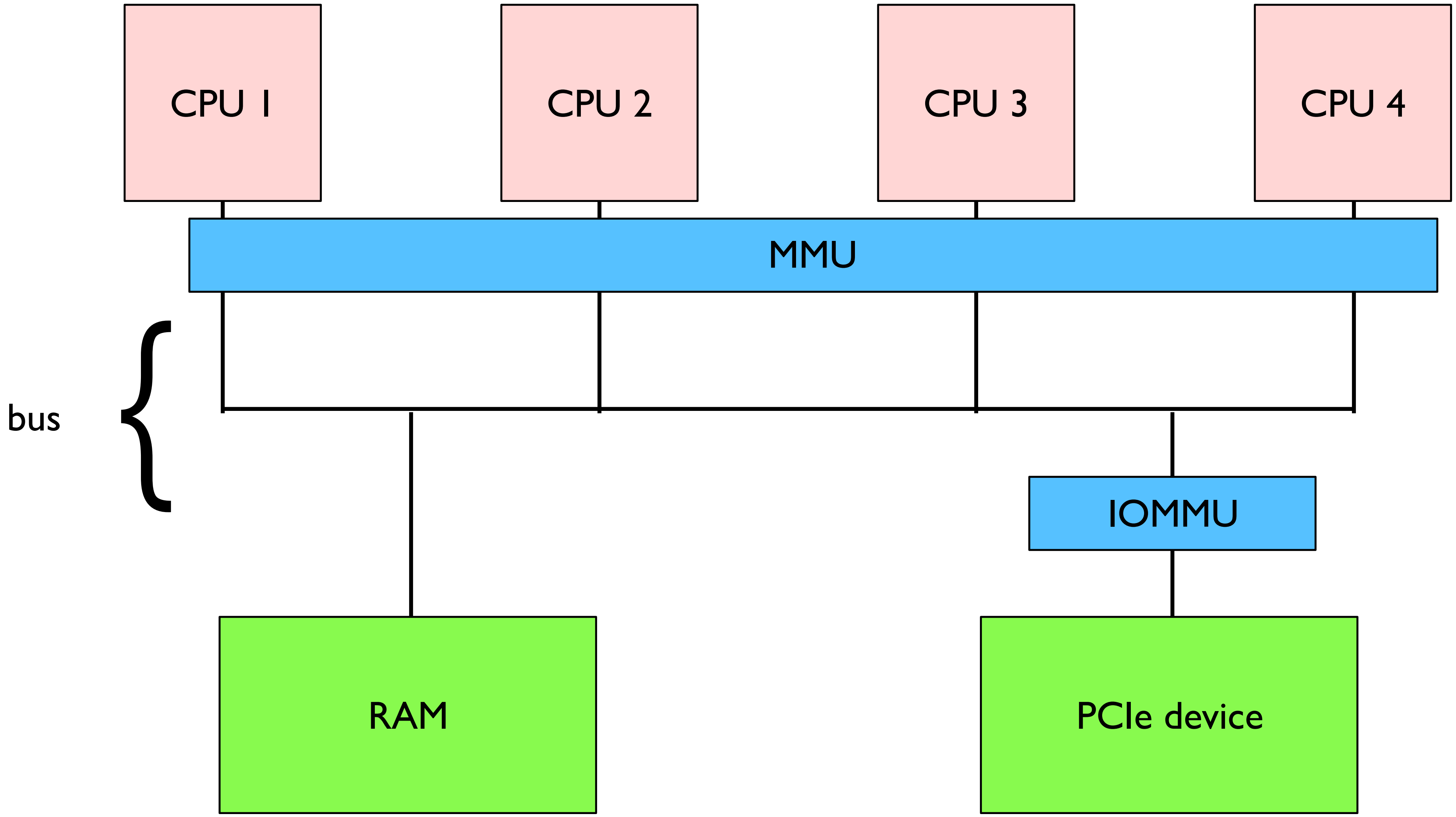


SR-IOV + IOMMU

Single-root I/O Virtualization

- Goal: Allow **direct execution** of I/O device access
- Challenge #1: how to partition a single device into multiple instances
  - SR-IOV allows a PCI device to expose multiple, separate memory-mapped I/O regions
- Challenge #2: How to prevent DMA from overwriting memory belonging to VMM or another guest
  - IOMMU: Provides paging translation across PCIe bus

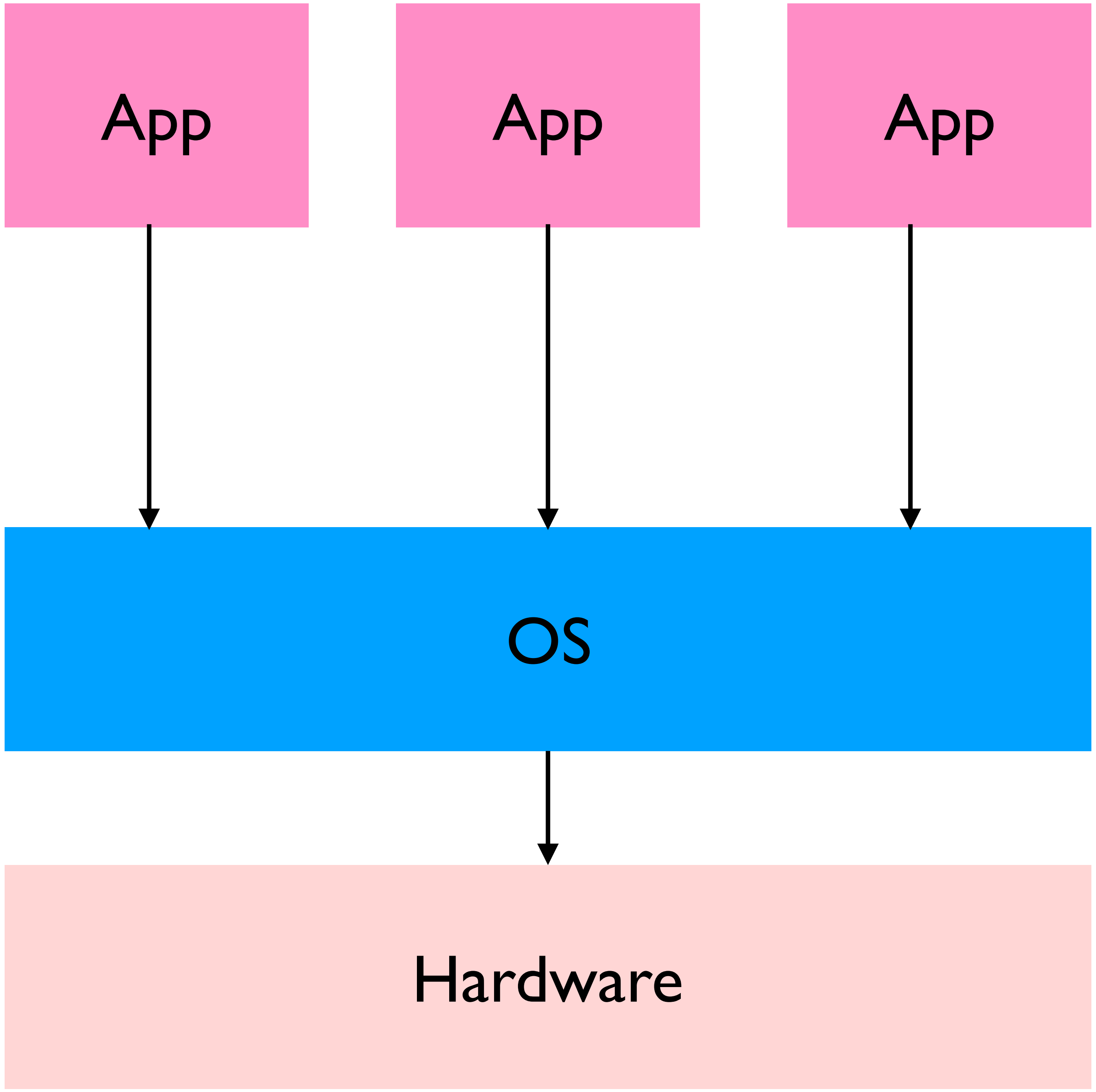
IOMMU



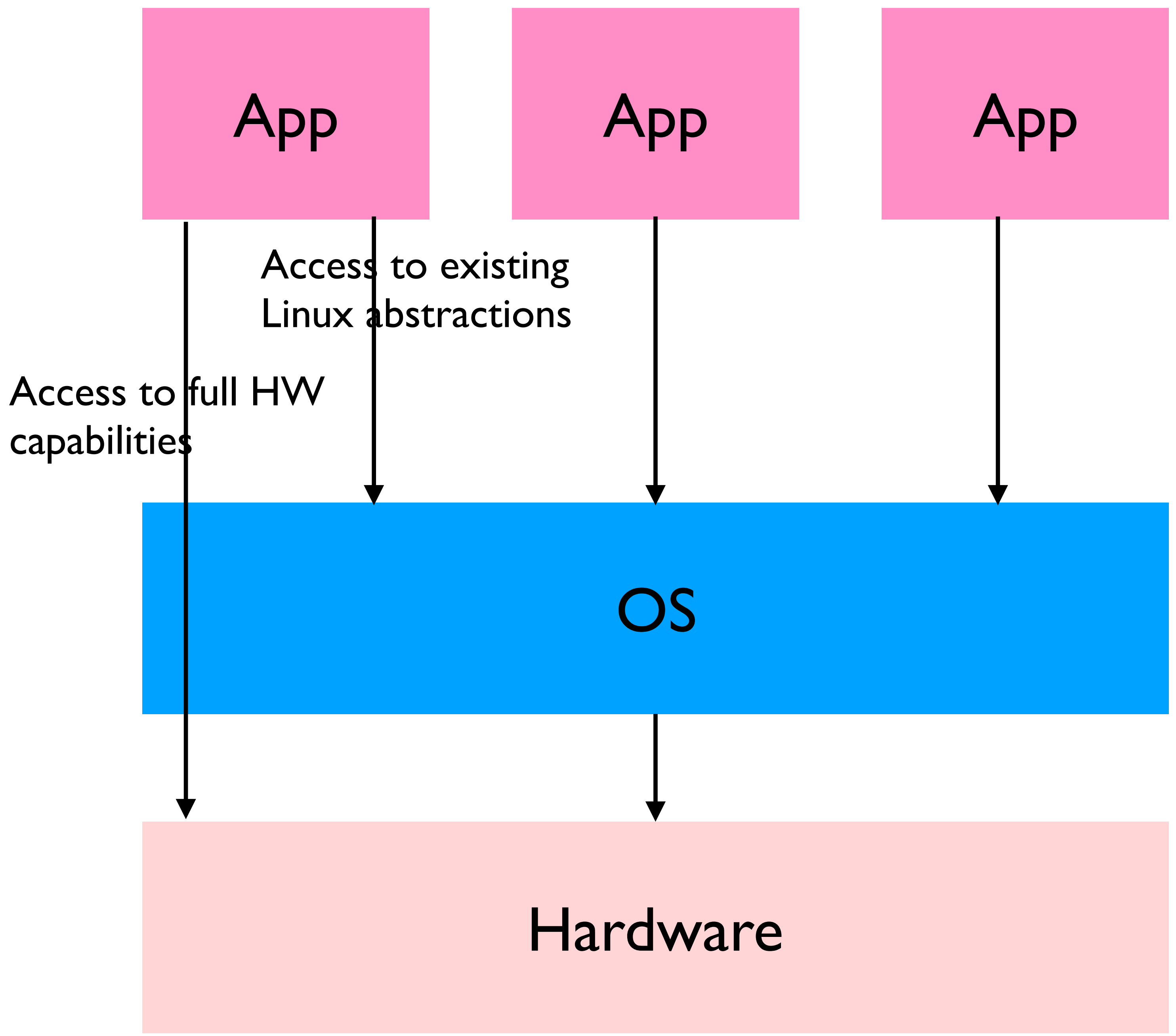
Big picture

- Direct execution reduces overhead
  - Avoids VM exits, trap-and-emulate, binary translation
- Enabled by three microarchitectural changes:
  - Intel VT-x: direct execution of most privileged instructions (e.g, IDT, GDT, CPL, EFLAG, etc.)
  - Intel EPT: direct execution of page table manipulation
  - IOMMU + SRIOV: direct execution of I/O interactions (e.g., network)

Operating systems today



What if you could give process access to raw hardware?



Dune

- Key idea: Use VT-x, EPT, etc, to support Linux processes instead of virtual machines
- Dune is a loadable Linux kernel module, makes it possible for an ordinary process to switch to “Dune mode”
- Dune mode processes can run alongside ordinary processes. Within a process, some threads can be Dune mode even if others aren’t

A Dune process

- Is still a Linux process
  - Has memory
  - Can make system calls
  - Is fully isolated
  - …
- But isolated with VT-X non-root mode
  - Rather than with CPL=3 and page table protections
- Memory protection via EPT
  - Dune configures EPT so processes can only access the same physical pages it would normally have access to.

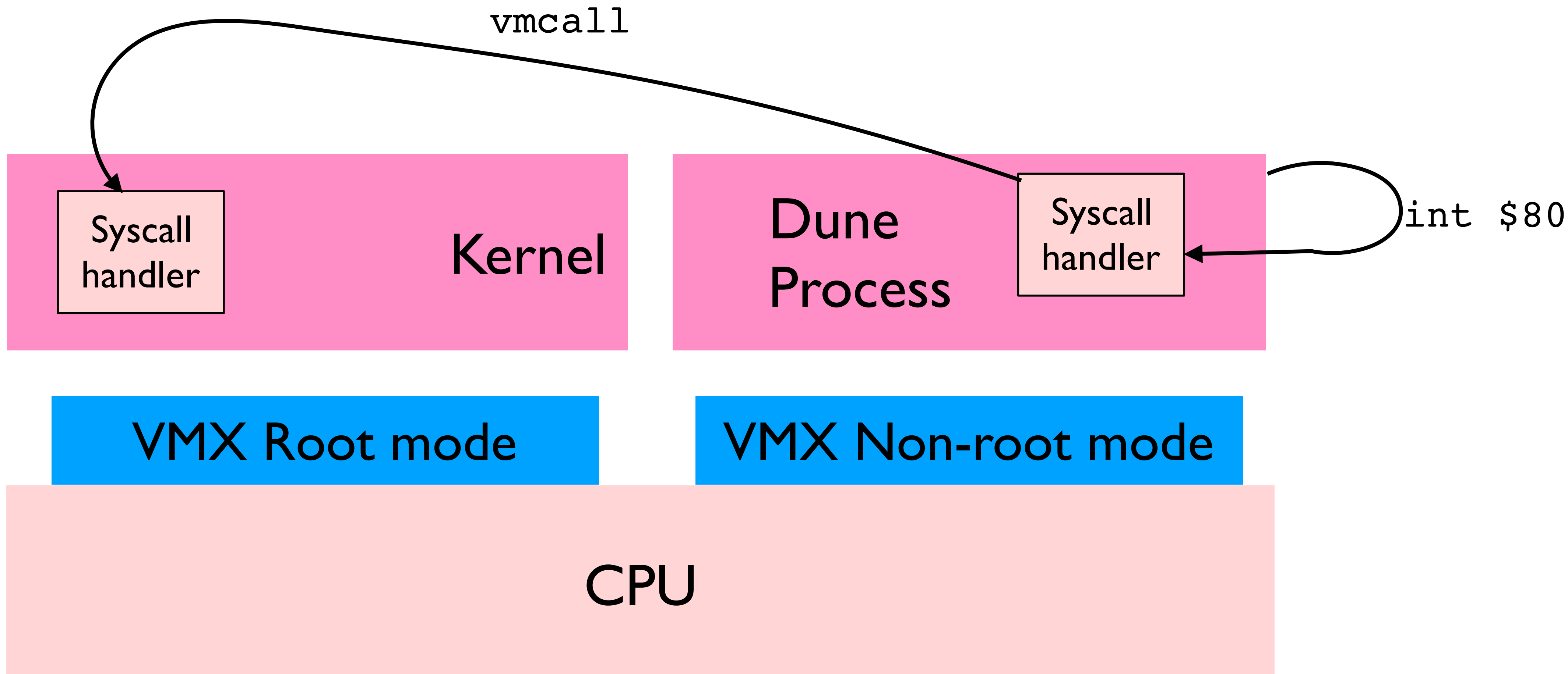
Why isolate a process with VT-x?

- Process can access all of Linux environment while also executing most privileged instructions
- User code now runs at CPL 0
- Process manages its own page table: `%CR3`
- Fast exceptions (e.g., page faults) via shadow IDT
  - Kernel crossings eliminated
  - Some interrupts configured to dispatch to non-root mode
  - Others configured to cause vmexit
- Can run sandboxed code at CPL 3
  - So process can act like a kernel!

How to perform a Linux system call from a Dune process?

- `int $80` just traps inside process at handler specified in shadow IDT
- `vmcall` instruction forces a VM exit
  - Dune module vectors exit into kernel system call table
- Challenge: compatibility
  - Existing code and libraries don't use `vmcall`
- Solution:
  - Shadow IDT handler forwards the system calls it catches using `vmcall`

How to perform a Linux system call from a Dune process?



Microbenchmarks: overheads

- Two sources of overhead:
  - VM exits and VM enters
  - EPT translations

	getpid	page fault	page walk
Linux	138	2,687	35.8
Dune	895	5,093	86.4

Table 2: Average time (in cycles) of operations that have overhead in Dune compared to Linux.

Microbenchmarks: speedups

- Large opportunities for optimization
  - Faster system-call interposition and traps
  - More efficient user-level virtual memory manipulation

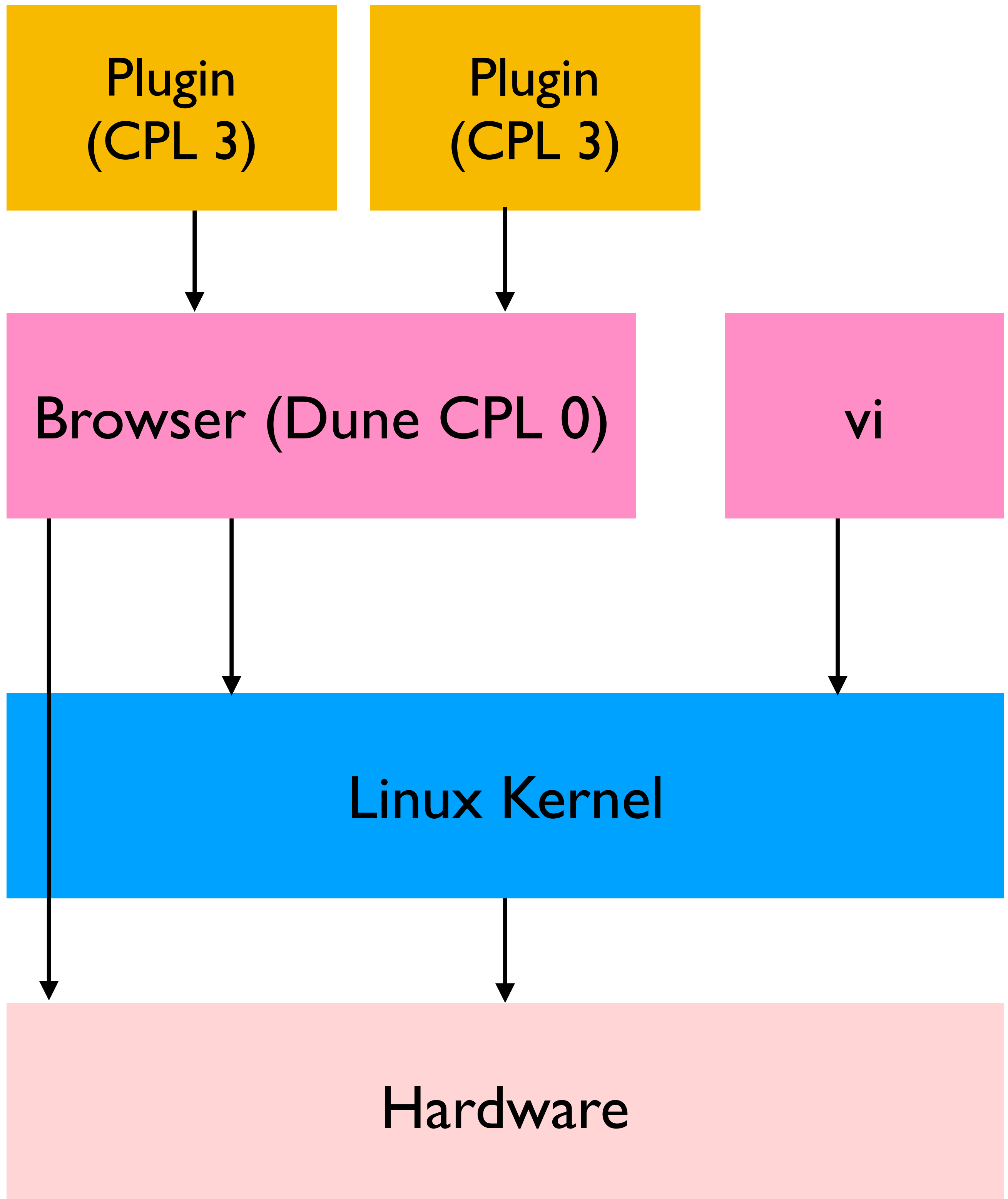
	Page fault		trap/prot1/unprot	protn/trap/unprot
	ptrace	**trap**	**appel1**	**appel2**
Linux	27,317	2,821	701,413	684,909
Dune	1,091	587	94,496	94,854

Table 3: Average time (in cycles) of operations that are faster in Dune compared to Linux.

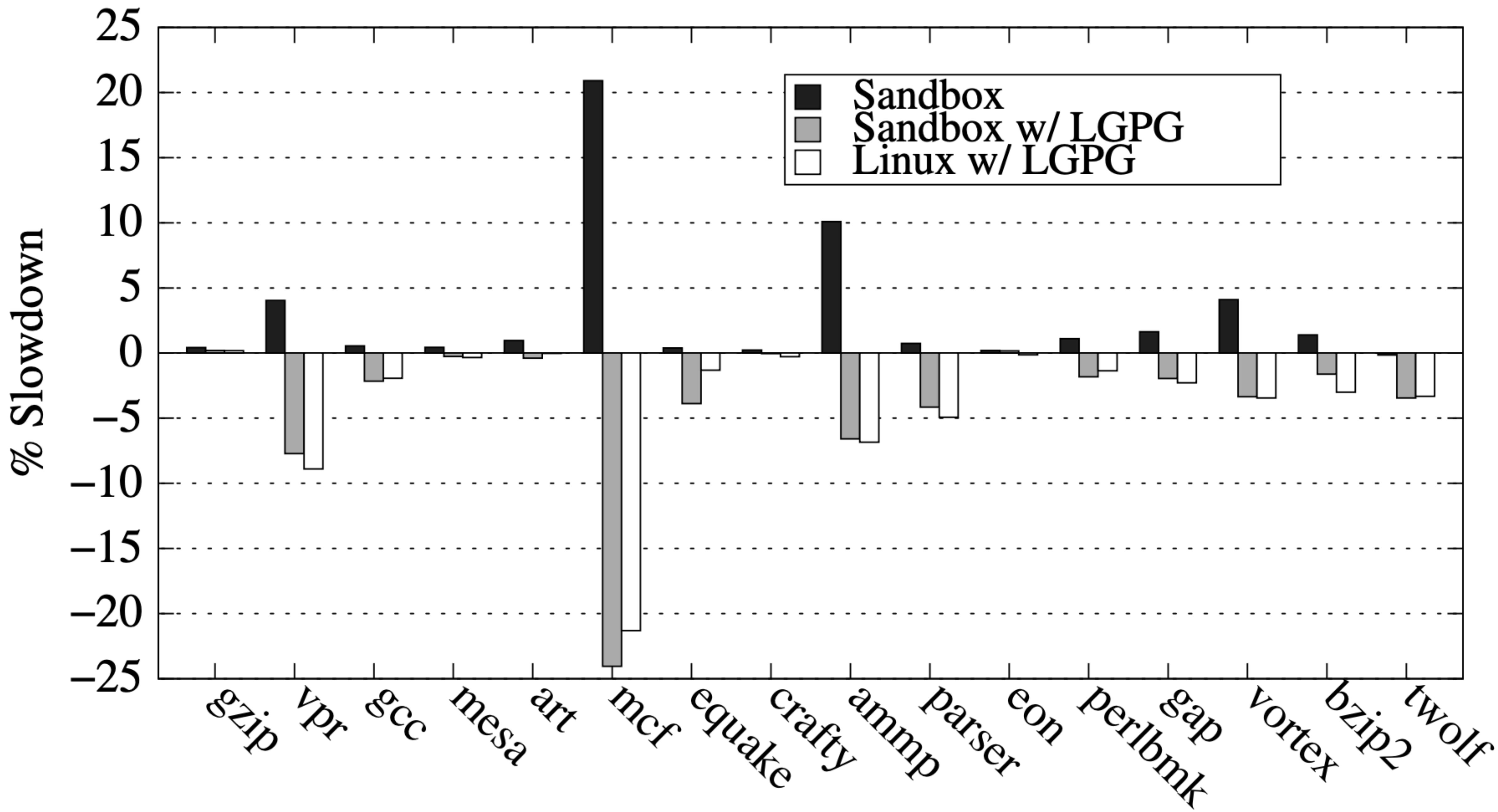
Example: sandboxed execution

- Suppose your browser wants to run a plugin
  - Could be buggy or malicious
- Need a way to execute plugin but limit:
  - System calls
  - Memory access
- Using Dune:
  - Browser is a Dune thread:
    - Run at CPL0
  - Create a Dune thread for plugin:
    - PTE_U mappings only for allowed access
    - Run at CPL3
    - Can run system calls but they trap to browser
      - Browser filters or emulates system calls

What if you could give process access to raw hardware?



Sandbox: SPEC2000 performance



- Only notable end-to-end effect is EPT overhead
  - Can be eliminated through the use of large pages

More thoughts on use cases

- Dune provides similar benefits to Exokernel
  - Raw access to paging hardware for Appel&Li paper
  - Speed improvements alone may make some ideas more feasible (e.g., GC)

- Each Dune thread can have a different page table!
  - E.g., sthreads: a mechanism for least privilege

Summary

- VT-x, EPT, and SR-IOV/IOMMU enable direct execution of (most) guest instructions
- Dune implements processes with VT-x and EPT rather than ordinary ring protection
- Dune processes can use both Linux system calls and privileged HW
  - Enables fast access to page table and page faults
  - Enables processes to build kernel-like functionality
    - E.g., sandboxing untrusted plugins in CPL3
    - Hard to do this at all in Linux, let alone efficiently

Question

- How can a Dune process be in ring 0, but non-VMX root?
- Why would a child process not want to be in Dune mode?
- Why would we have some threads be in Dune mode, and others not?
- Is Dune emulating the privileged calls to, e.g., the TLB, or is it really changing the values in the hardware?
- What is `ioctl` (used by a process to enter Dune mode)?
- If Dune module is like VMM and Dune process like guest OS, how can Dune module "override" the normal host VMM