Virtualization II

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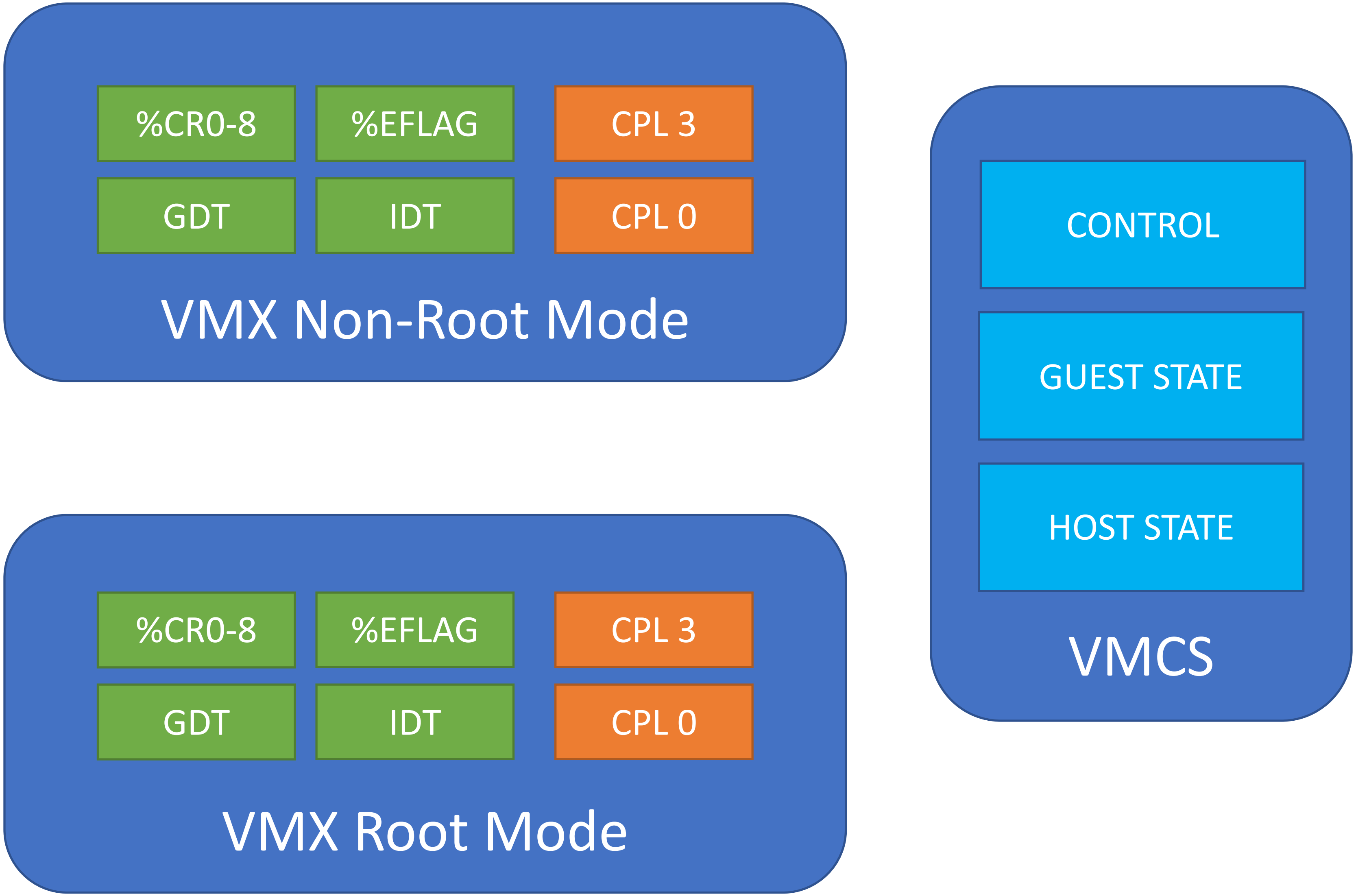
Plan for today

- Last lecture: Virtualization basics
  - A VMM is an operating system that maintains a machine-like interface instead of a process interface
  - Many compelling reasons to use virtualization
  - Originally, virtualization wasn’t believed to be possible on x86
  - VMware introduced binary translation solution
- Today: Recent developments
  - More detailed discussion of HW support for virtualization
  - Safe user-level access to privileged CPU features

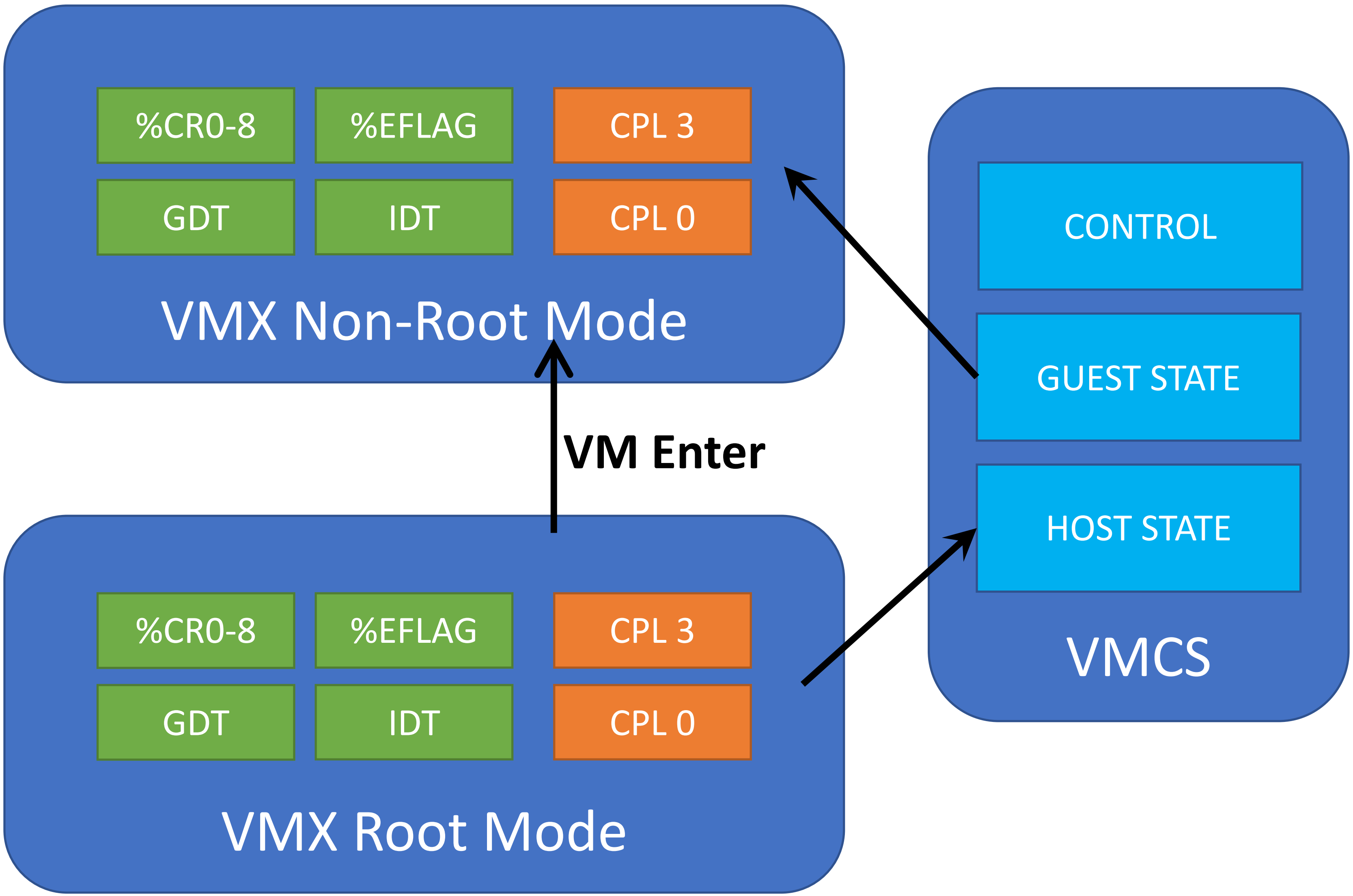
Intel VT-x

- Makes x86 hardware “virtualizable” under Popek and Goldberg definition
- Goal: **Direct execution** of most privileged instructions
- Introduces two CPU modes, kind of like ring protection
  - VMX Root Mode: For running VMM (host)
  - VMX Non-root Mode: For running VMs (guest)
  - But each mode has its own rings (CPL0 – CPL3)
- In-memory structure called VMCS stores privileged register state and control flags

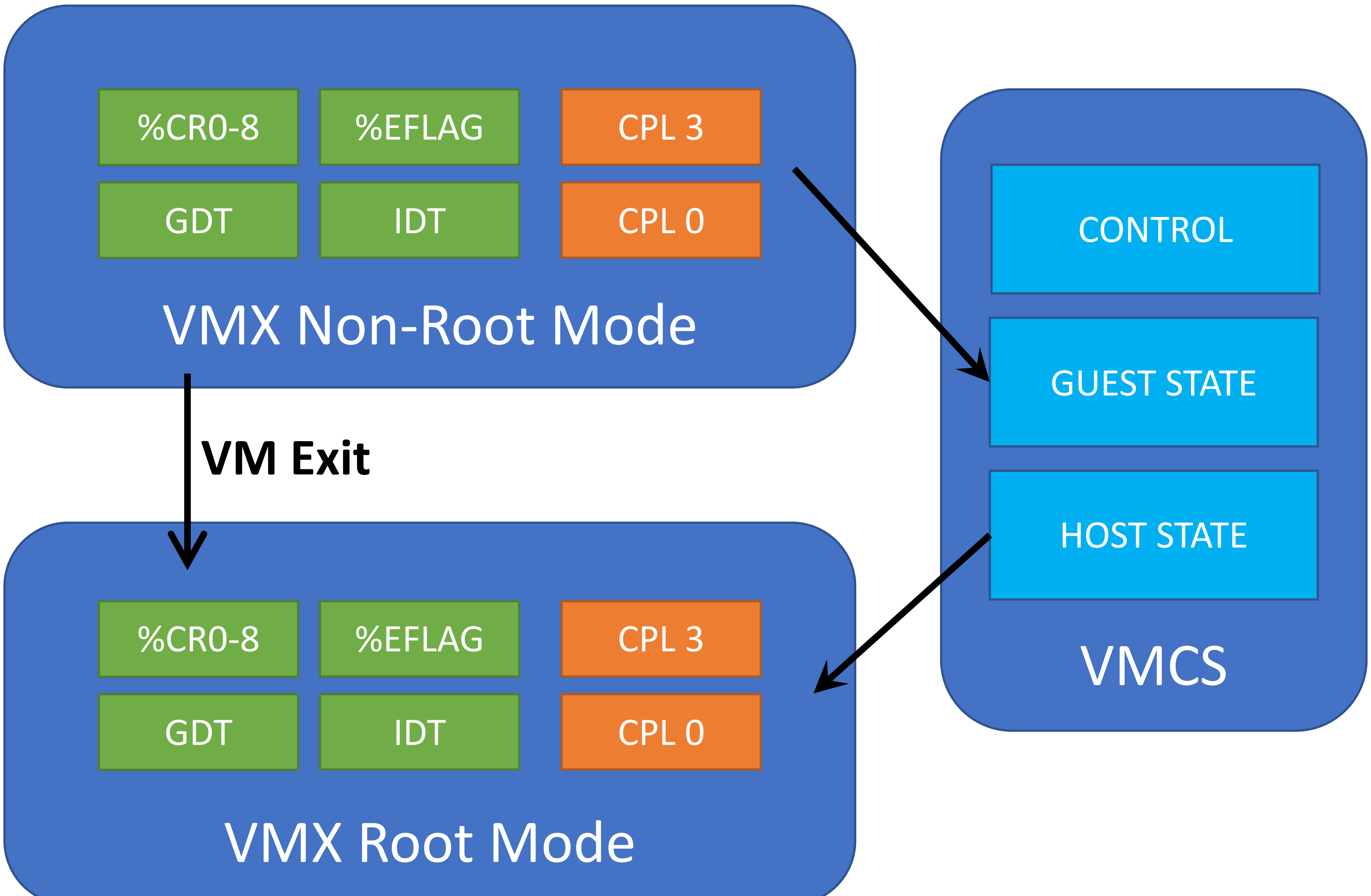
Intel VT-x


%CR0-8
%EFLAG
CPL 3
GDT
IDT
CPL 0
VMX Non-Root Mode
CONTROL
GUEST STATE
HOST STATE
VMCS
%CR0-8
%EFLAG
CPL 3
GDT
IDT
CPL 0
VMX Root Mode

Intel VT-x: VM Enter



Intel VT-x: VM Exit



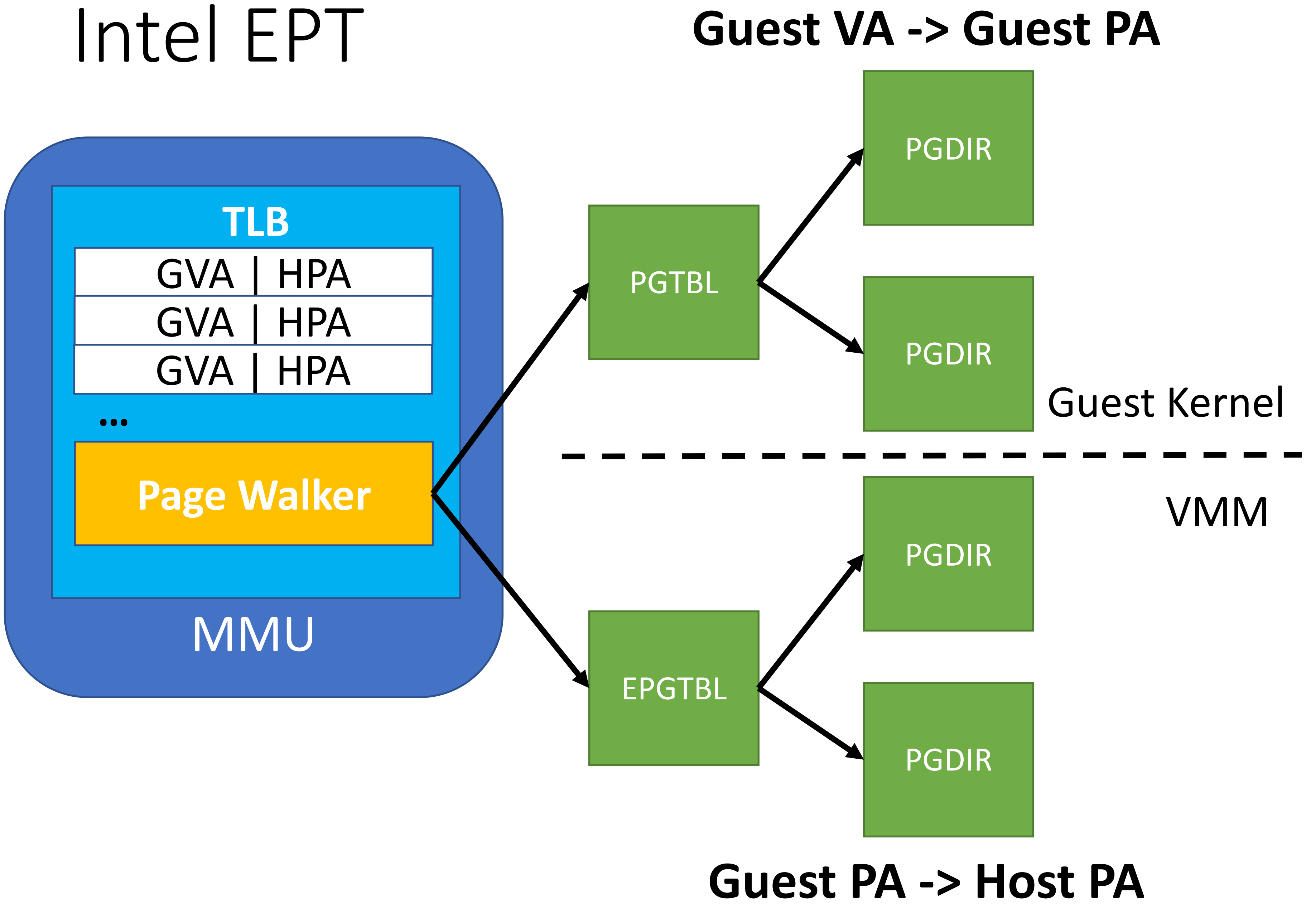
VM Enter and VM Exit

- Transitions between VMX Root Mode and VMX Non-root Mode
- VM Exit
  - VMCALL instruction, EPT Page Faults, some trap and emulate (configured in VMCS)
- VM Enter
  - VMLAUNCH instruction: Enter VMX Non-root Mode for a new VMCS
  - VMRESUME instruction: Enter VMX Non-root Mode for the last VMCS (faster)
- Typical VM Exit/Enter is ~200 cycles on modern HW

Intel EPT (nested paging)

- Goal: **Direct execution** of guest page table interactions
  - Reads and write 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

Intel EPT


Guest VA -> Guest PA
TLB
GVA | HPA
GVA | HPA
GVA | HPA
...
Page Walker
MMU
PGTBL
PGDIR
PGDIR
Guest Kernel
VMM
PGDIR
EPGTBL
PGDIR
Guest PA -> Host PA

Q: What's the worst case page walk time with EPT enabled?

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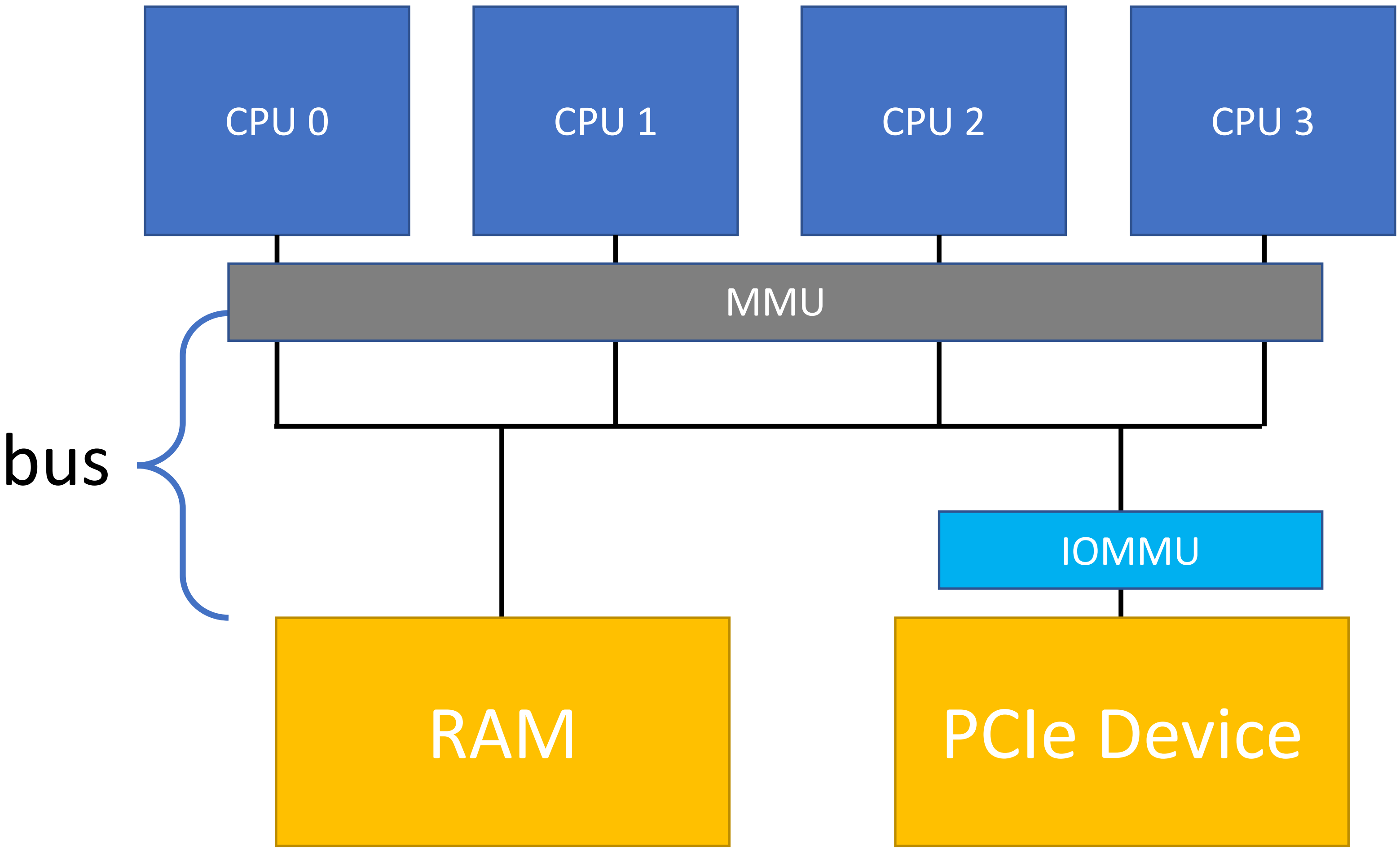
- O(N^2): Each page table level could require an EPT page walk
- But in practice CPU hardware caches the first couple levels of page table and EPT, so usually O(N)

Q: What’s faster EPT or Shadow Page Tables?

SR-IOV + IOMMU

- Goal: Allows **direction execution** of I/O device access
- Challenge #1: How to partition a single device into multiple instances
  - SR-IOV: Allows a PCIe device to expose multiple, seperate 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

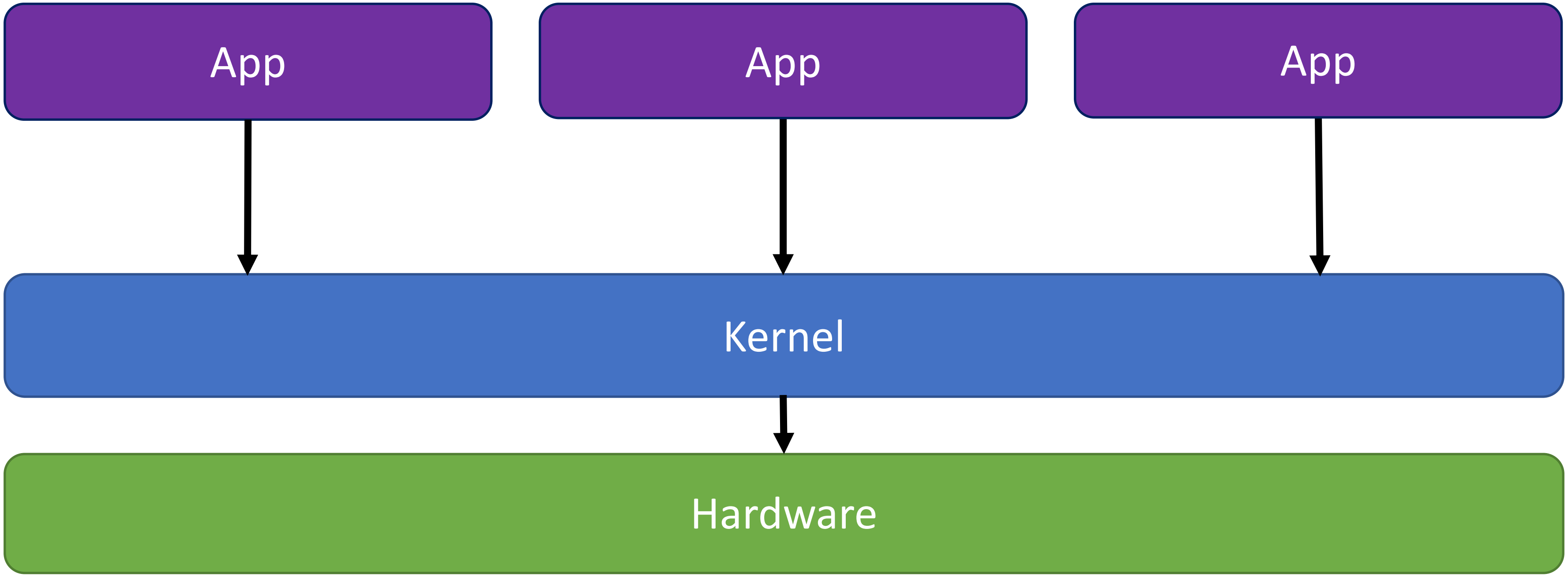
IOMMU



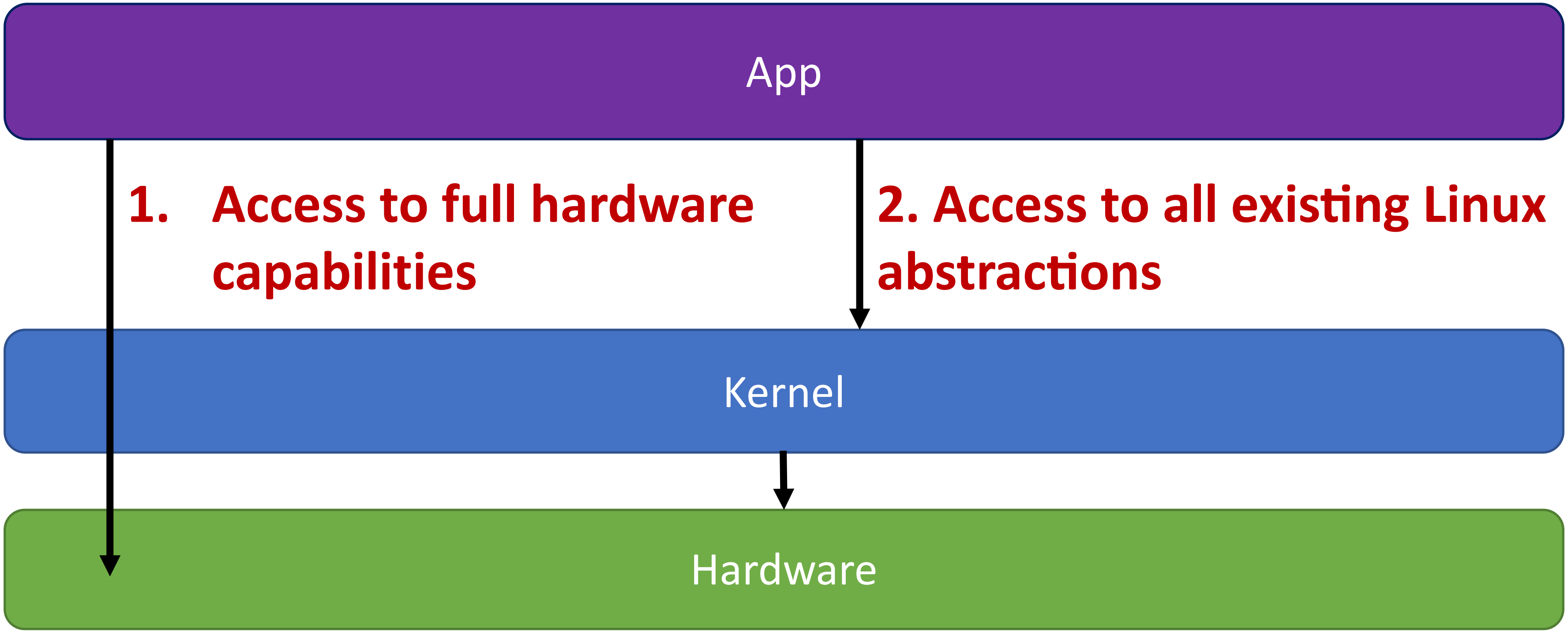
Big picture

- 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, ring protection, EFLAG, etc.)
  - Intel EPT: direct execution of page table manipulation
  - IOMMU + SRIOV: direct execution of I/O interactions (e.g. disk, network, etc.)

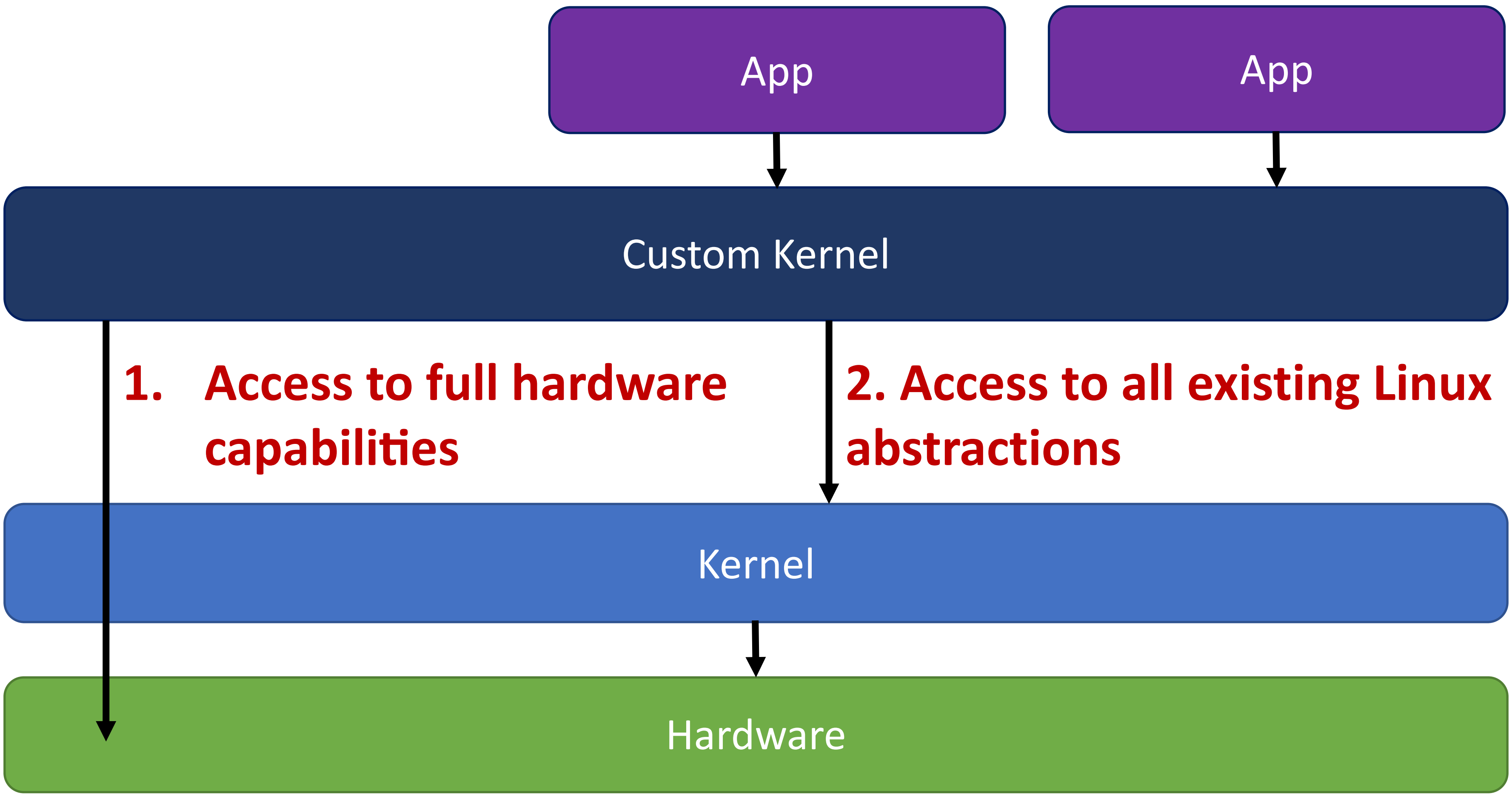
Operating systems today



What if you could give a process access to raw hardware?

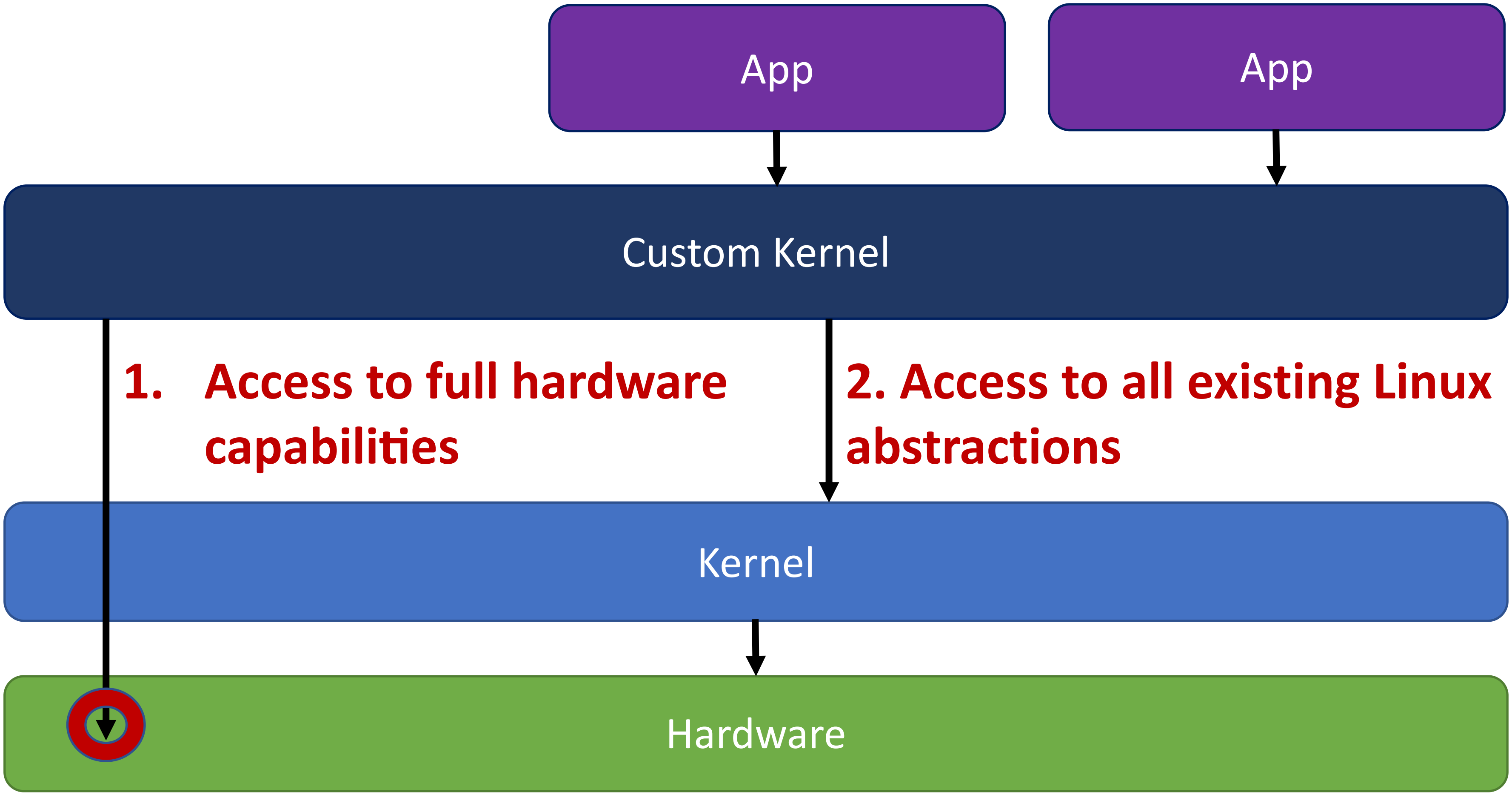


Could build new OS on top of Linux



Key idea: Using Linux means access through system calls

But still have to maintain process isolation



Dune

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

A dune process

- Is still a process
  - has memory, can make Linux system calls, is fully isolated, etc.
- 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 process 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 directly executing most privileged instructions
- User code now runs at CPL 0
- Process can manage its own page table via %CR3
- Fast exceptions (e.g. page faults) via shadow IDT
  - Kernel crossings eliminated
- Can run sandboxed code at CPL 3
  - So process can act like a kernel!

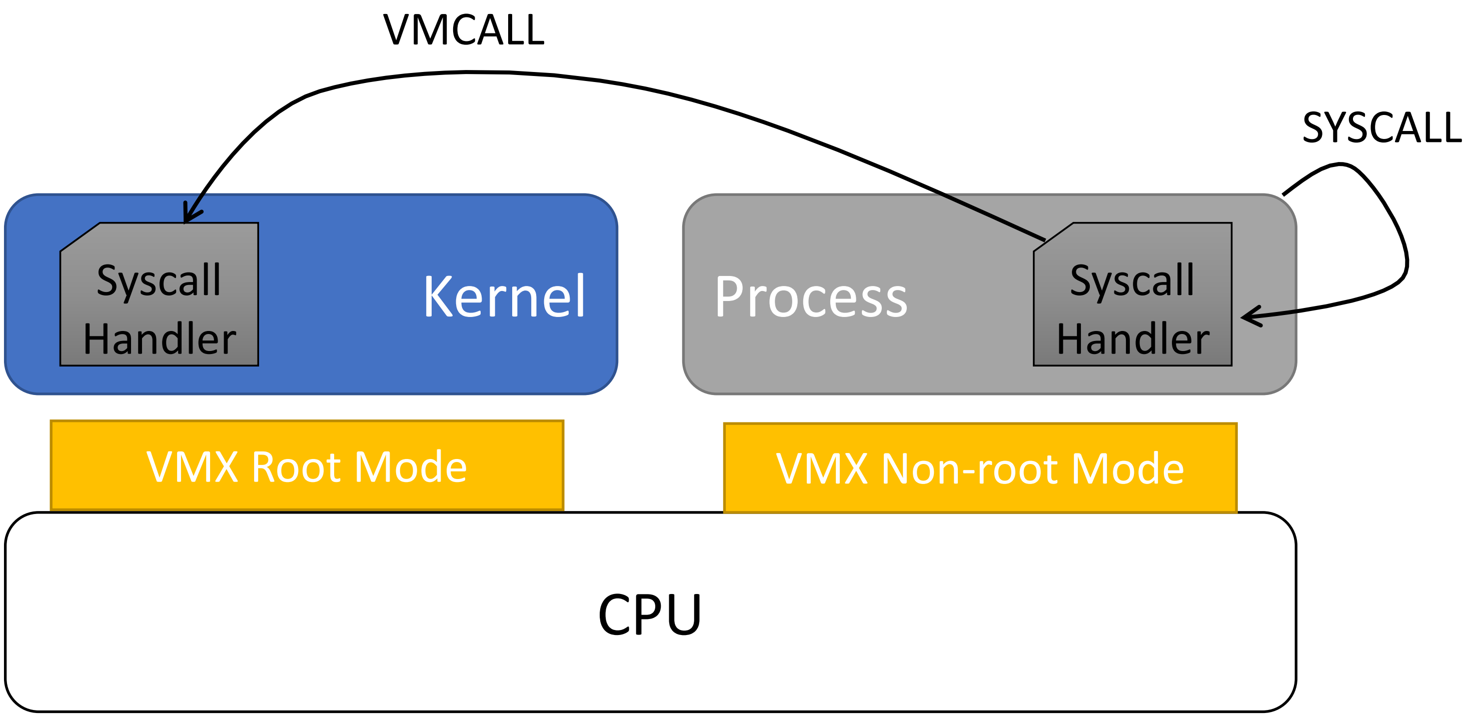
How to perform a Linux system call in a Dune process?

- INT $80 just traps inside process at handler specified in shadow IDT

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



Microbenchmarks: Overheads

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

(cycles)	Getpid	Page fault	Page walk
Linux	138	2,687	36
Dune	895	5,093	86

Microbenchmarks: Speedups

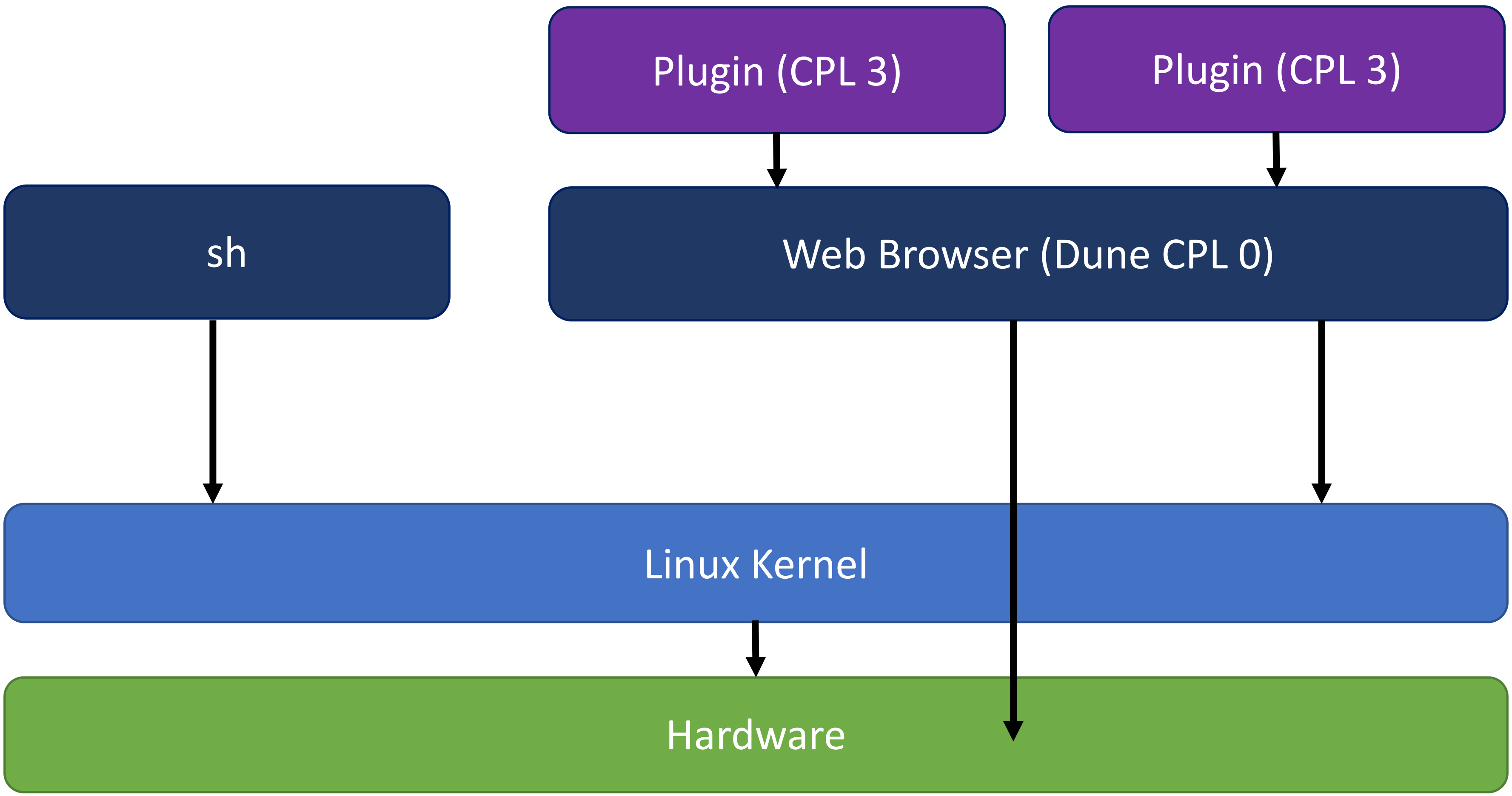
- Large opportunities for optimization
  - Faster system call interposition and traps
  - More efficient user-level virtual memory manipulation

(cycles)	ptrace (getpid)	trap	Appel 1 (TRAP, PROT1, UNPROT)	Appel 2 (PROTN, TRAP, UNPROT)
Linux	27,317	2,821	701,413	684,909
Dune	1,091	587	94,496	94,854

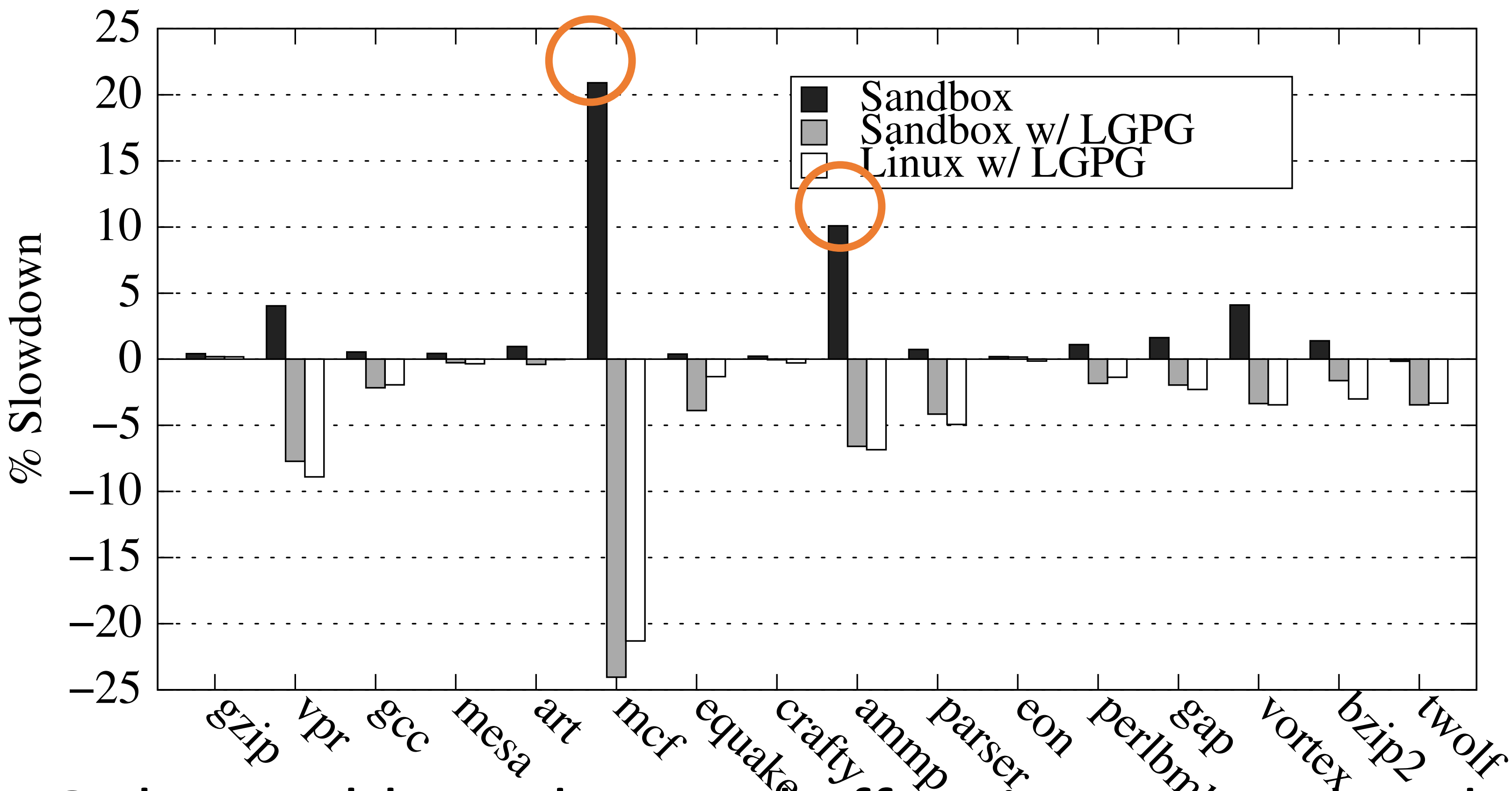
Example: Sandboxed execution

- Suppose your browser wants to run a plugin
  - It could be buggy or malicious
- Need a way to execute plugin but limit system calls and memory access
- Using Dune:
  - Could create a page table with PTE_U mappings for allowed access and ~PTE_U for prohibited access
  - Run browser in CPL0 and plugin in CPL3
  - Plugin can run system calls but they trap into browser
  - Browser filters or emulates system calls

Sandboxing diagram



Sandbox: SPEC2000 performance

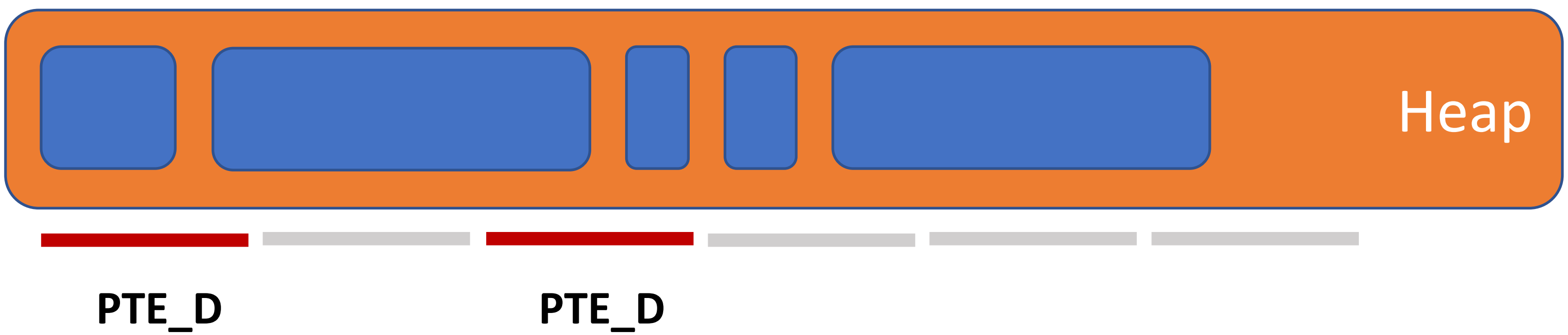


- Only notable end-to-end effect is EPT overhead
- Can be eliminated through use of large pages

Example: Garbage collection (GC)

- GC is mostly about tracing pointers to find live data
  - set a mark flag in every reached object
  - Any object not marked is dead and can be freed
- Boehm collector is concurrent GC:
  - Mutator runs in parallel with tracer -- with no locks
  - At some point the tracer has followed all pointers
    - But mutator might modify pointers in already traced objects
    - Solution: pause mutator briefly, look at all pages modified since tracer has started
- How does Dune help?
  - Clear all PTE dirty bits (PTE_D) at start of GC
  - Scan for set PTE dirty bits to detect written pages

Example: Garbage collection (GC)



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 (GC, DSM, etc.)
- Each Dune thread can have a different page table!
  - E.g. sthreads, a mechanism for least privilege

Conclusion

- VT-x, EPT, and SR-IOV/IOMMU enable direct execution of 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