Virtualization

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Computer Science & Artificial Intelligence Lab
M.I.T.

Abstractions

Devices
Materials
Atoms

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Digital design
Combinational and sequential circuits

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Computer architecture
Processors, caches, pipelining

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Software

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Instruction set + memory

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Bits, Logic gates

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Abstractions

Computer programs

Virtual machines

Computer systems
Operating systems, virtual memory, I/O

Instruction set + memory

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Processors, caches, pipelining

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Evolution in Number of Users

IBM 1620
1959

<u>Single User</u>

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<u>Single User</u>	<u>Multiple Users</u>
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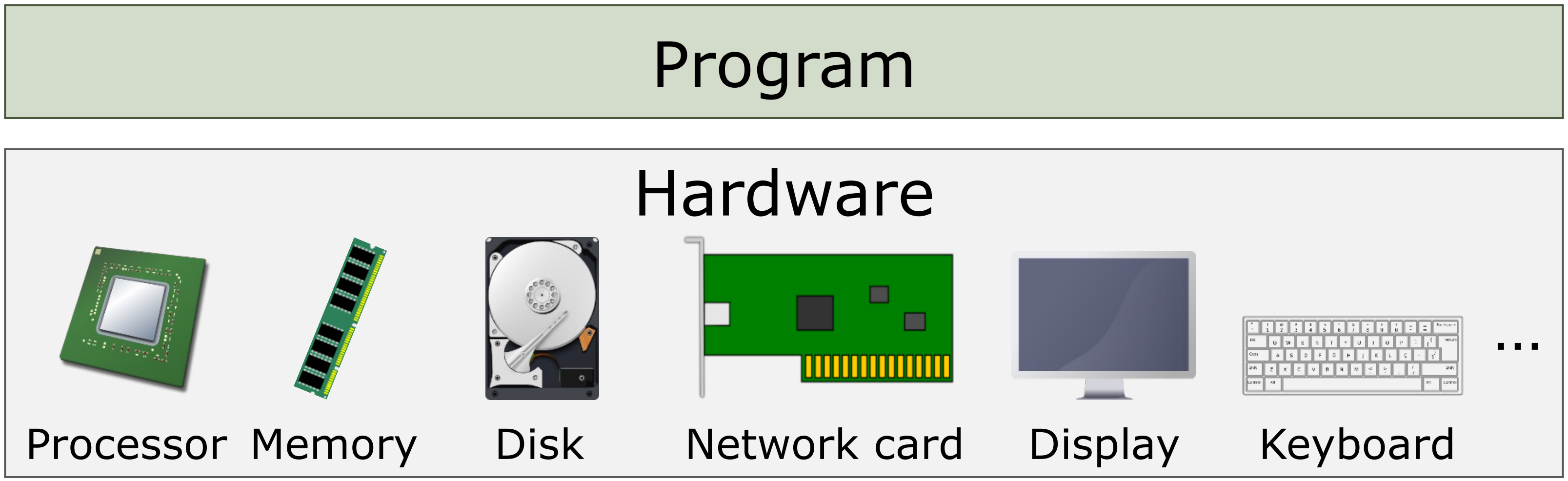
Runtime loaded with program	OS for sharing resources	OS for sharing resources	Multiple OSs

Single-Program Machine



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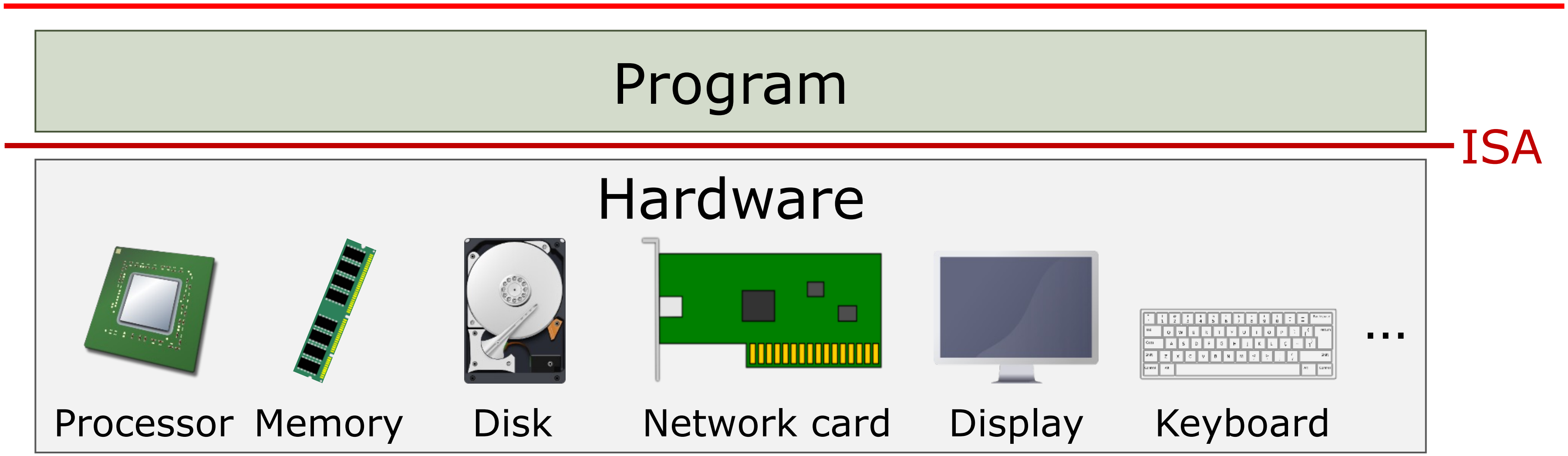

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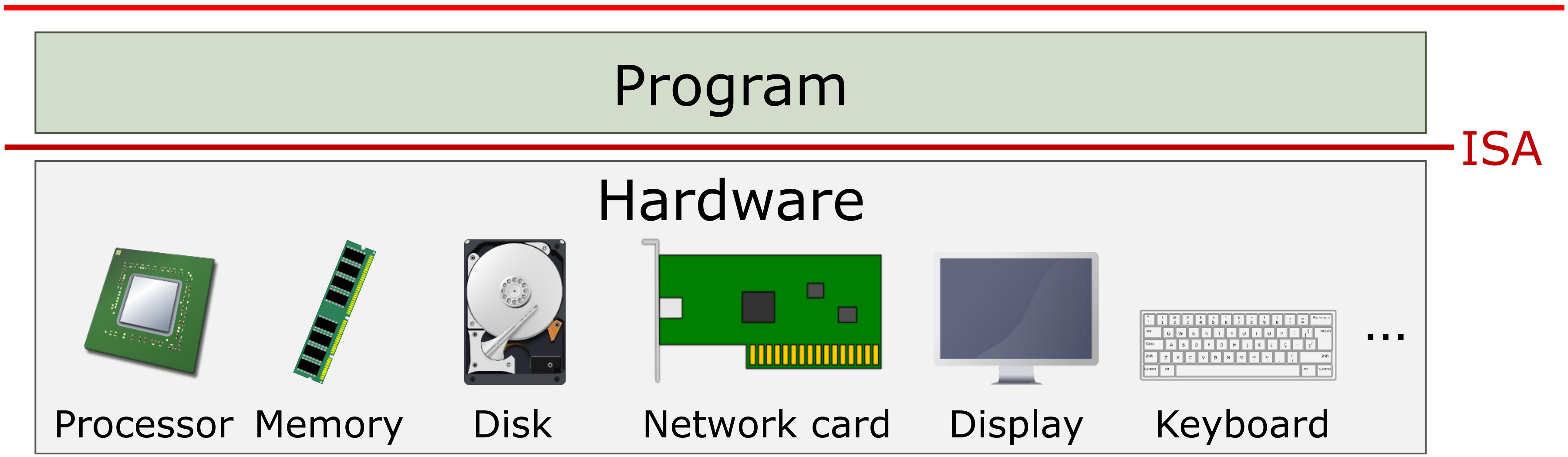
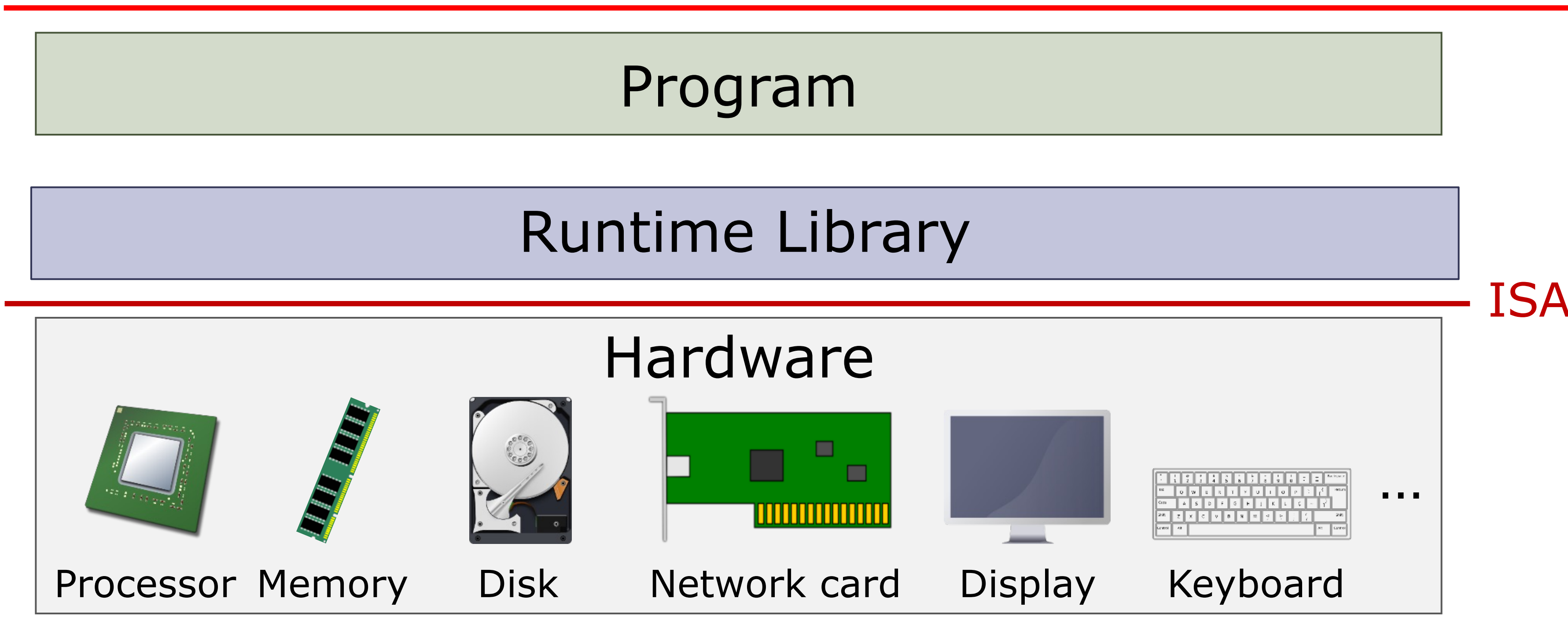


- Hardware executes a single program and has direct and complete access to all hardware resources
- The ISA is the interface between software and hardware:
  - Program counter
  - General purpose registers
  - Memory

Single-Program Machine (with RTL)



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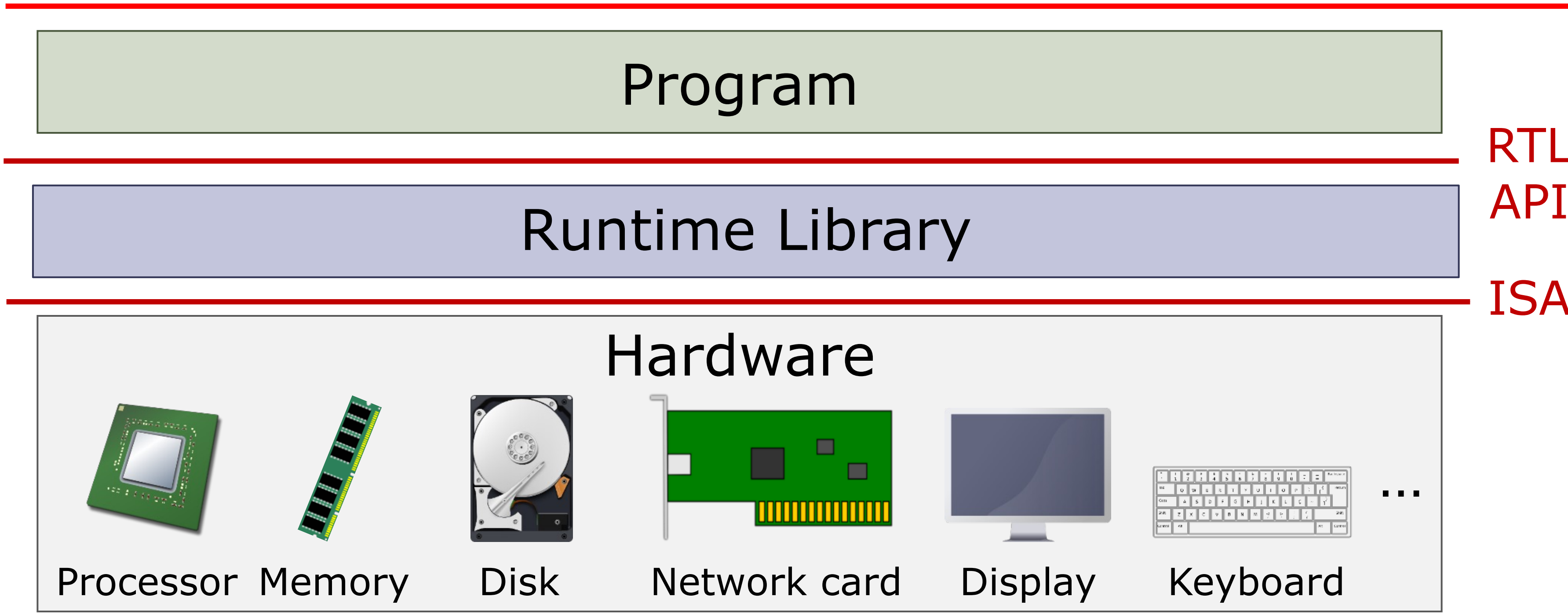

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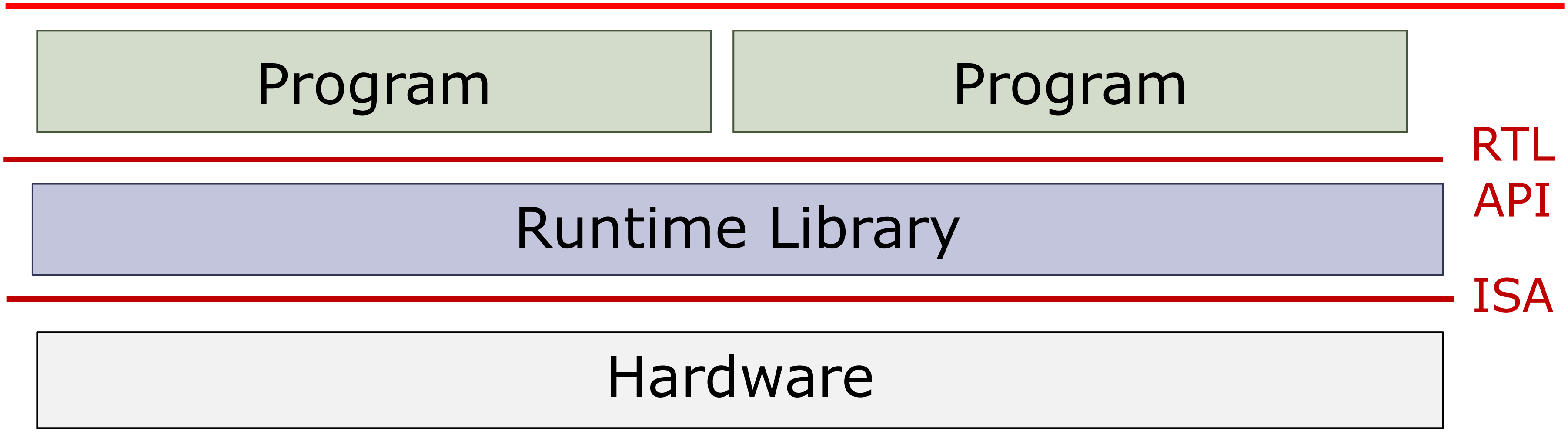

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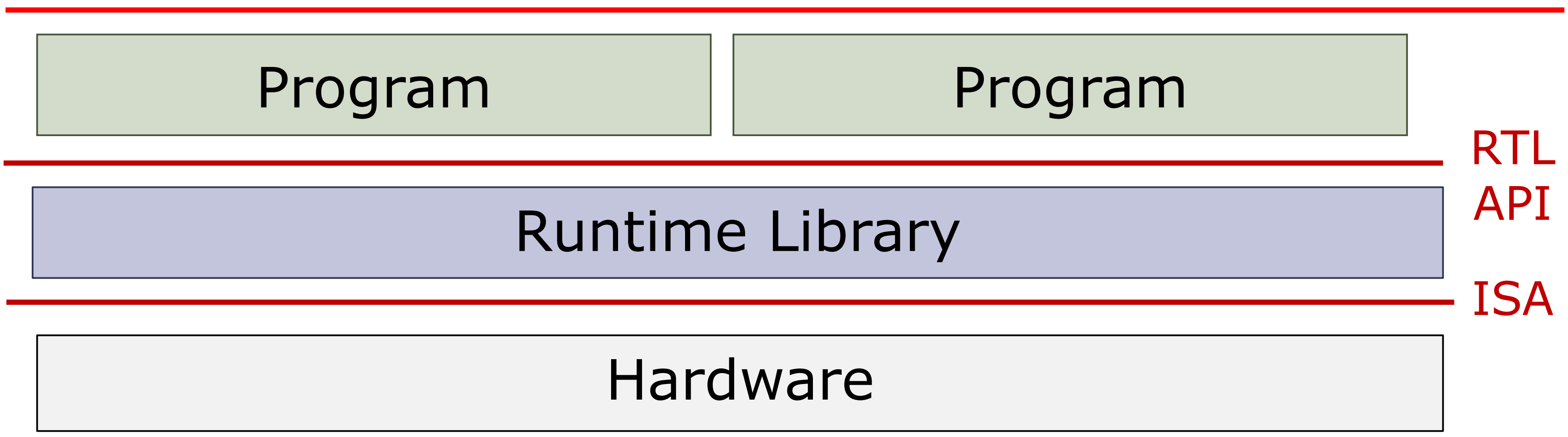

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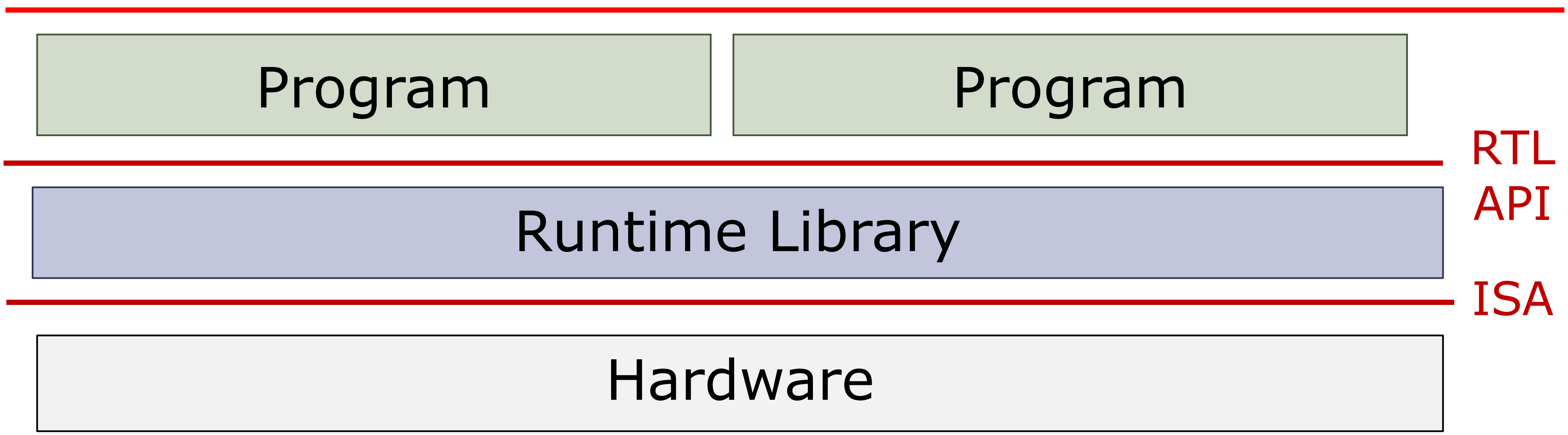
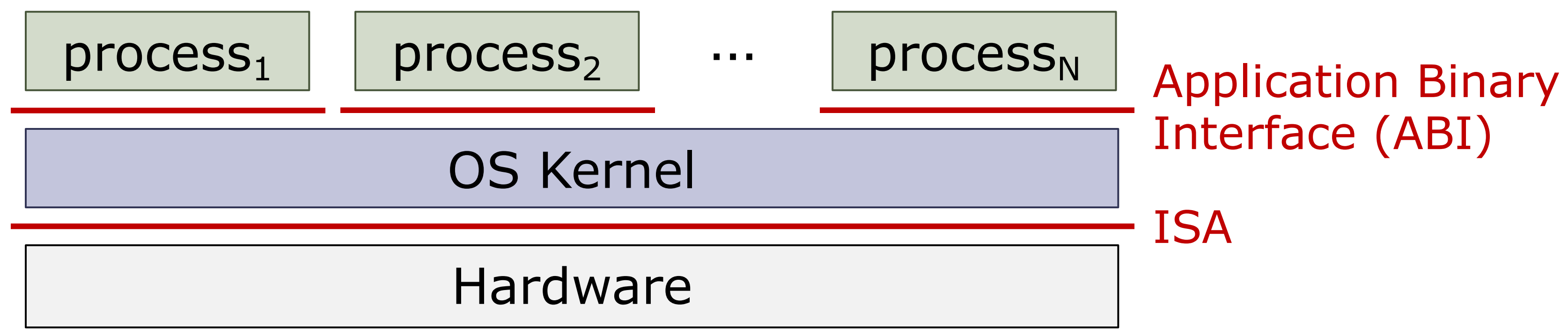


Any problems? security

Operating Systems



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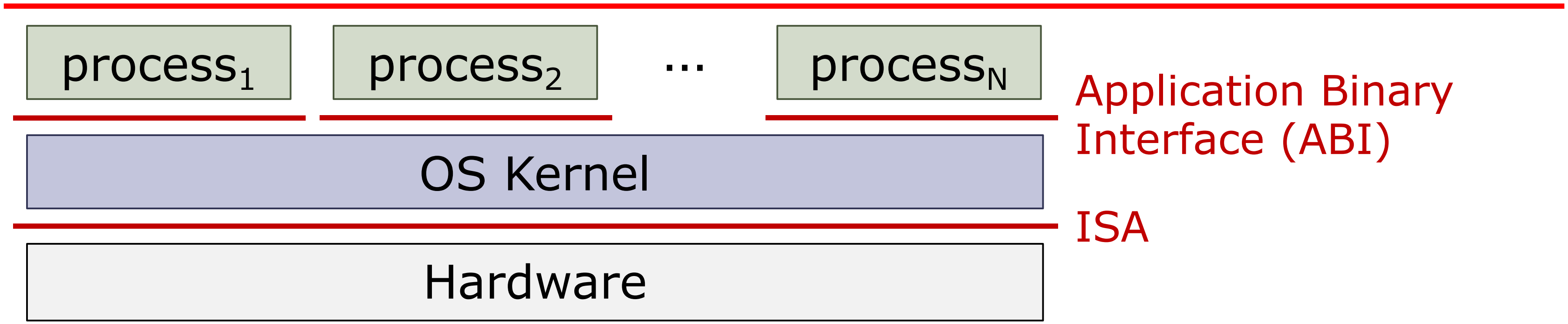

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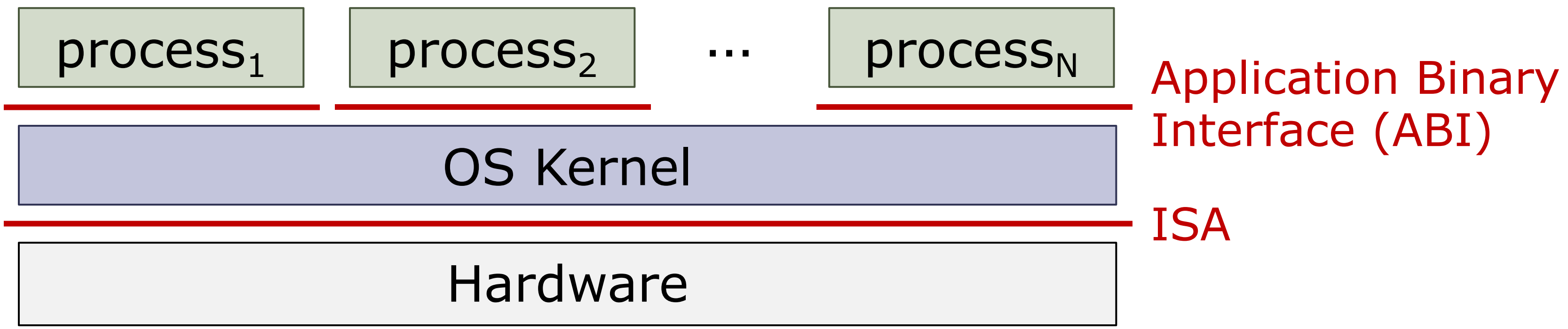

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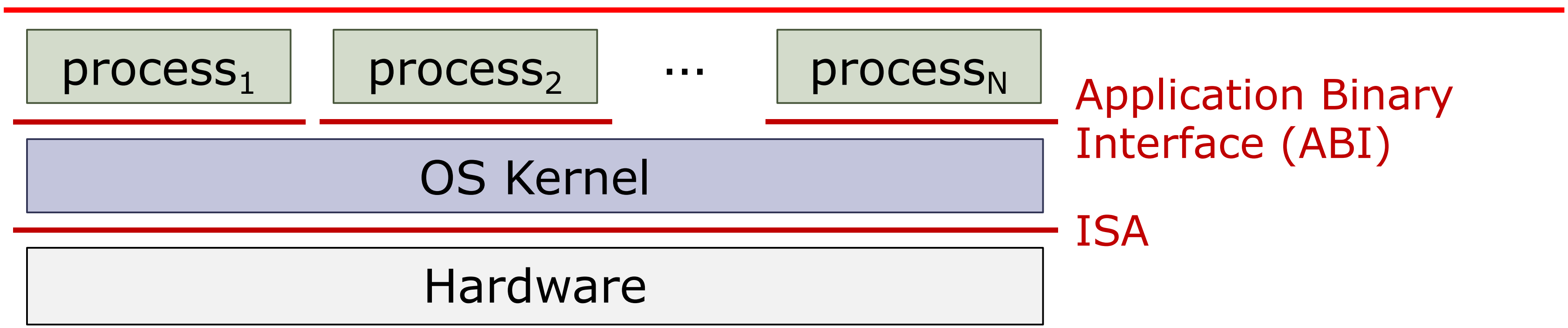

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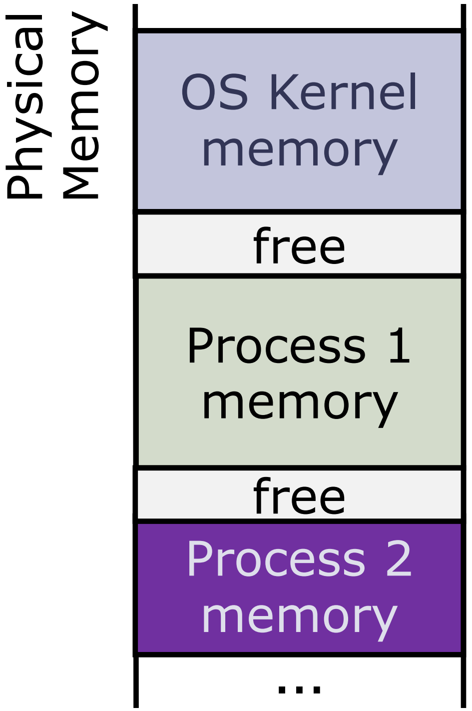
  - Protection and privacy: Processes cannot access each other's data

Operating System Mechanisms

- The OS kernel provides a private address space to each process
  - Each process is allocated space in physical memory by the OS
  - A process is not allowed to access the memory of other processes



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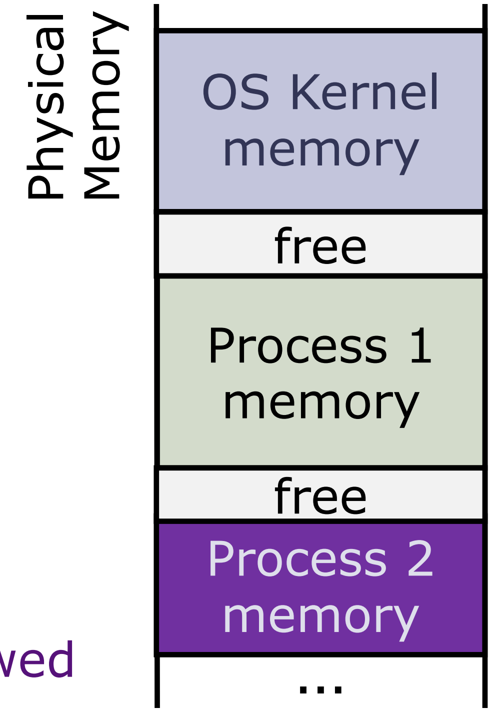

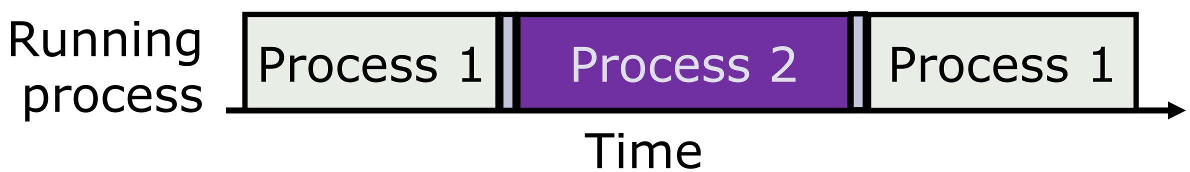

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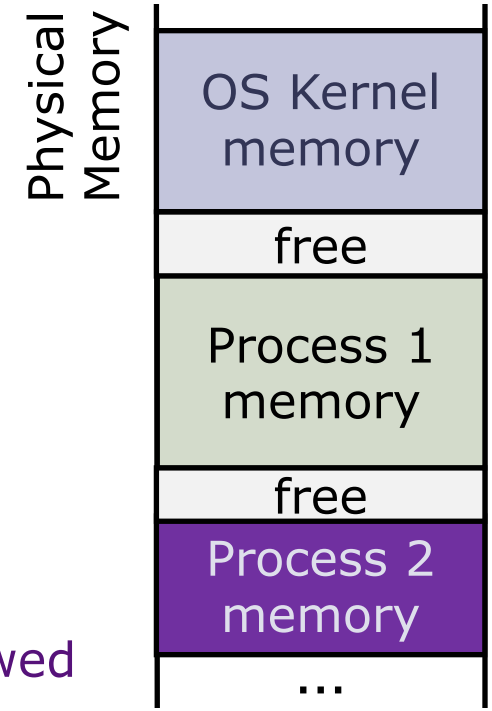

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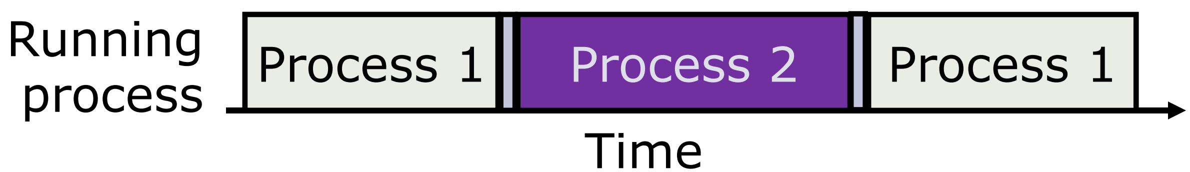
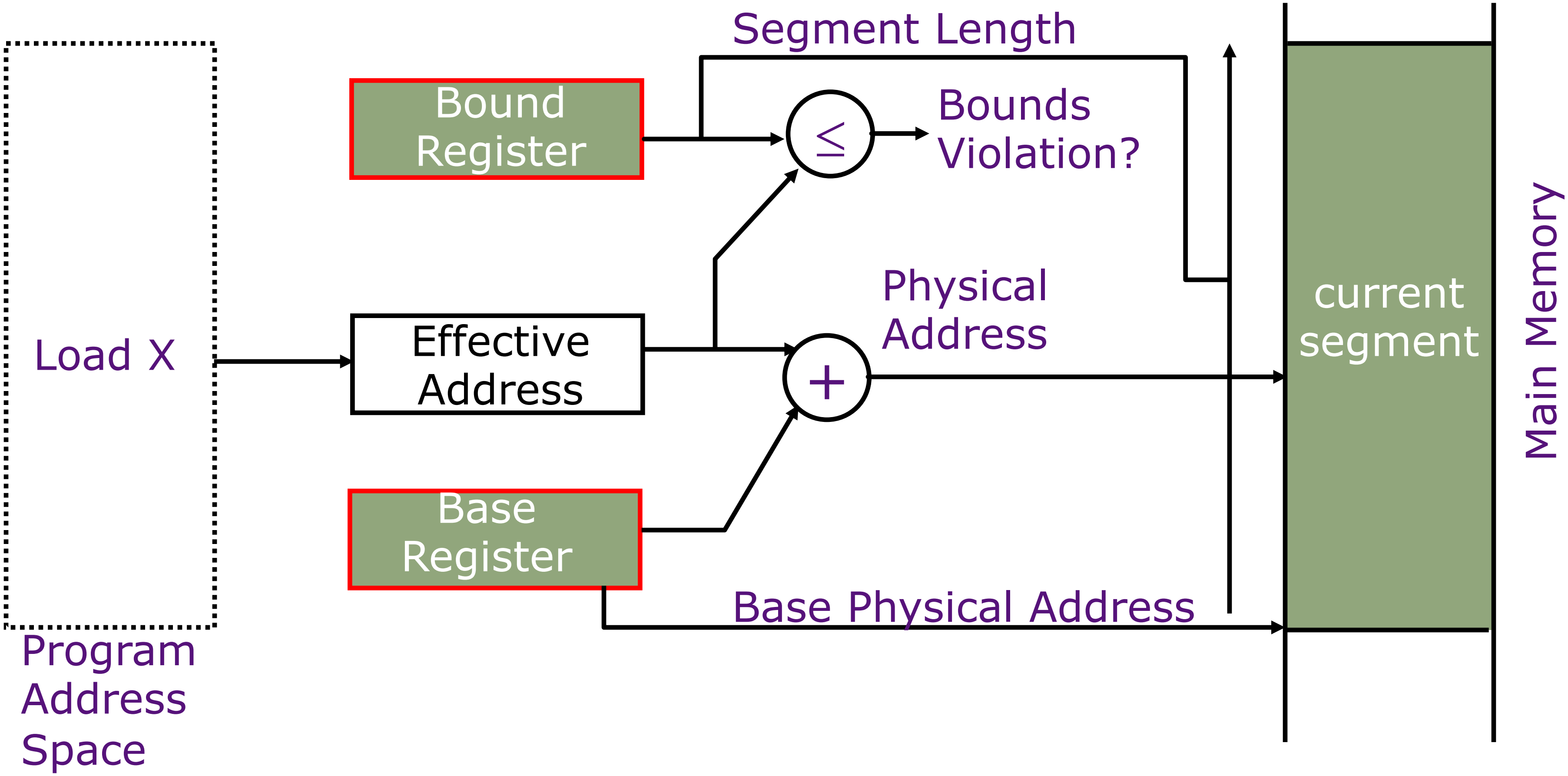


- The OS kernel lets processes invoke system services (e.g., access files or network sockets) via system calls

Simple Base and Bound Translation



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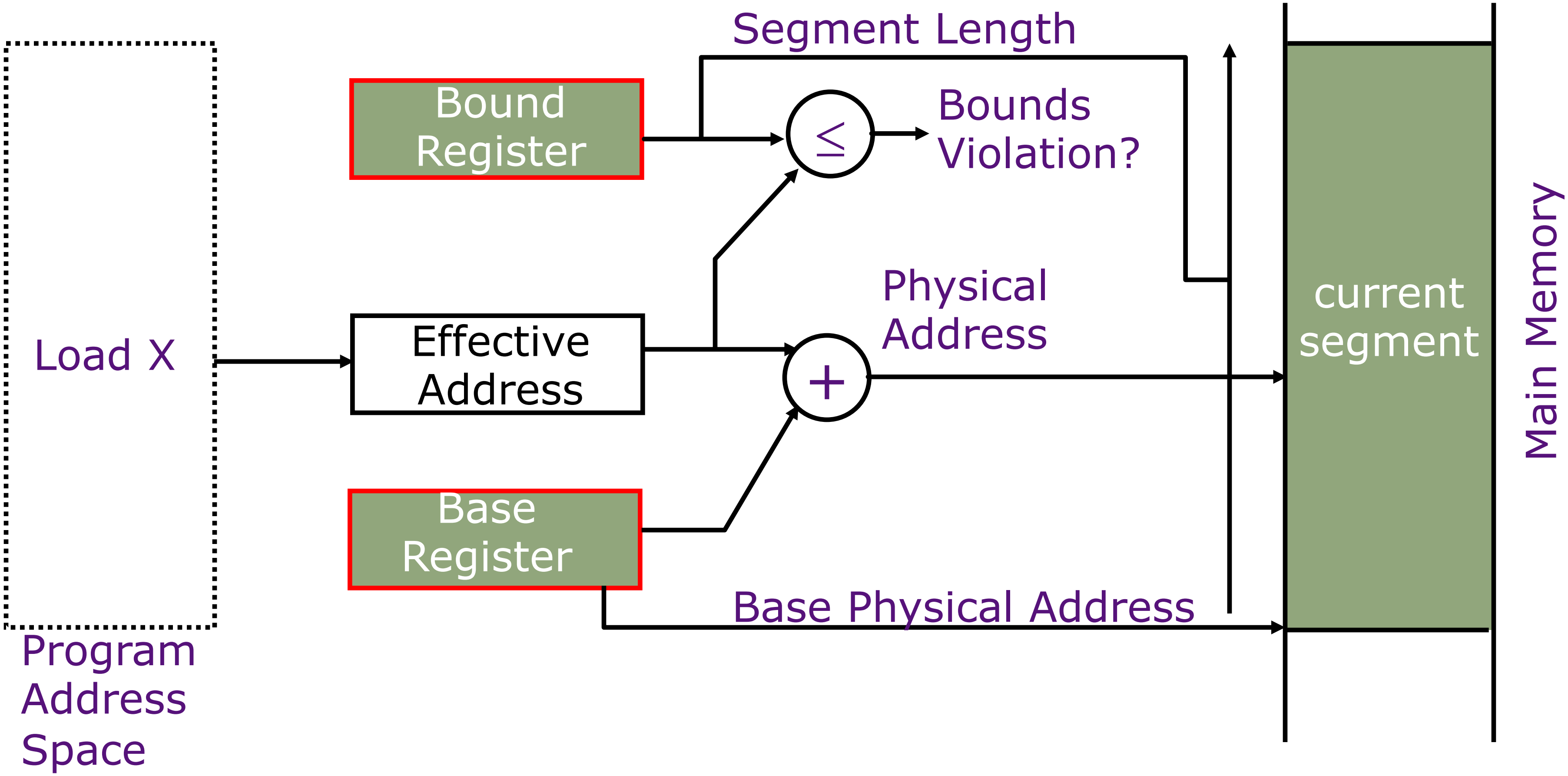

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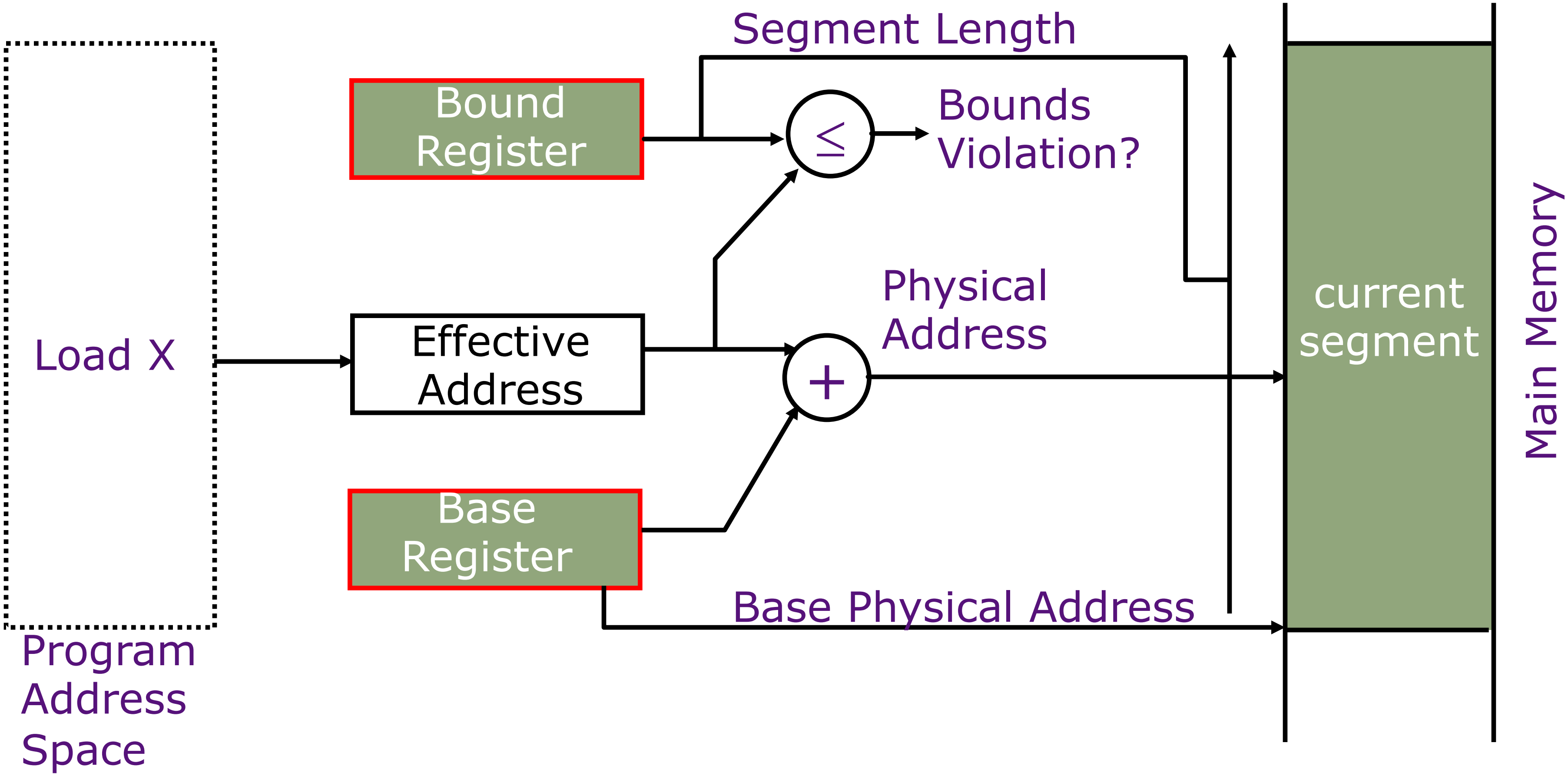

Introduce a new privileged mode in which the base and bounds registers are visible/accessible.

Protecting Memory

Page Table Entry

Valid<31>	Prot<30:27>	Modified<26>	OS<25:21>	PFN<20:0>

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TLB Entry

Tag	Valid	Prot	PFN

Protecting Memory

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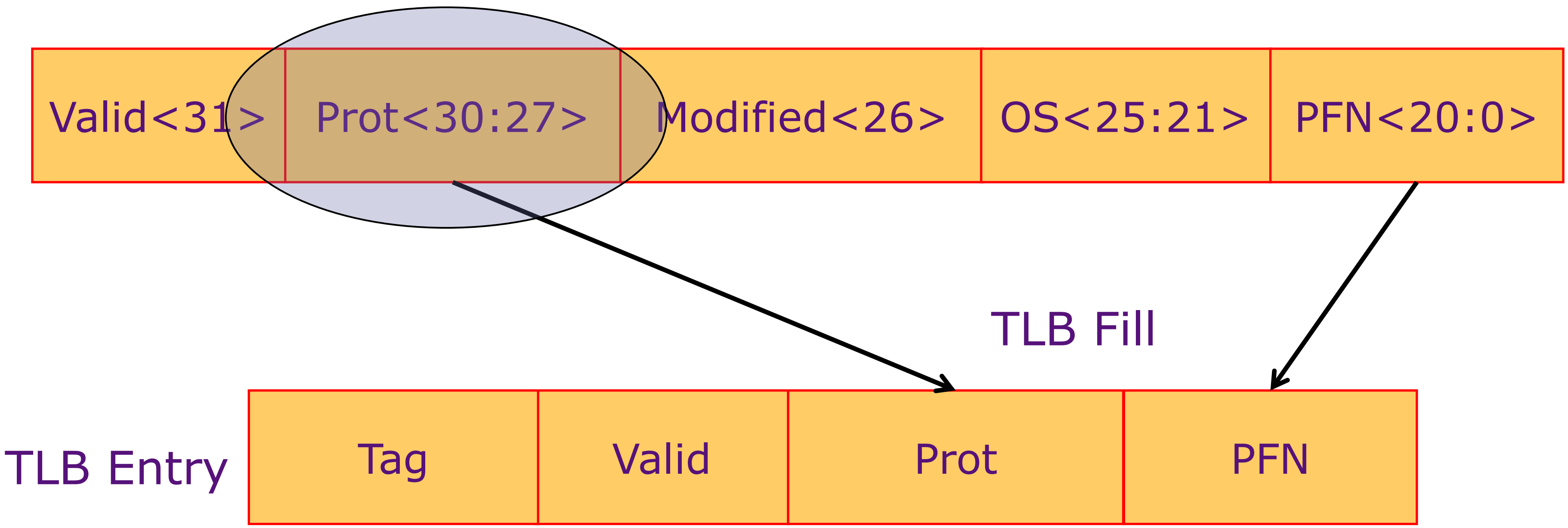

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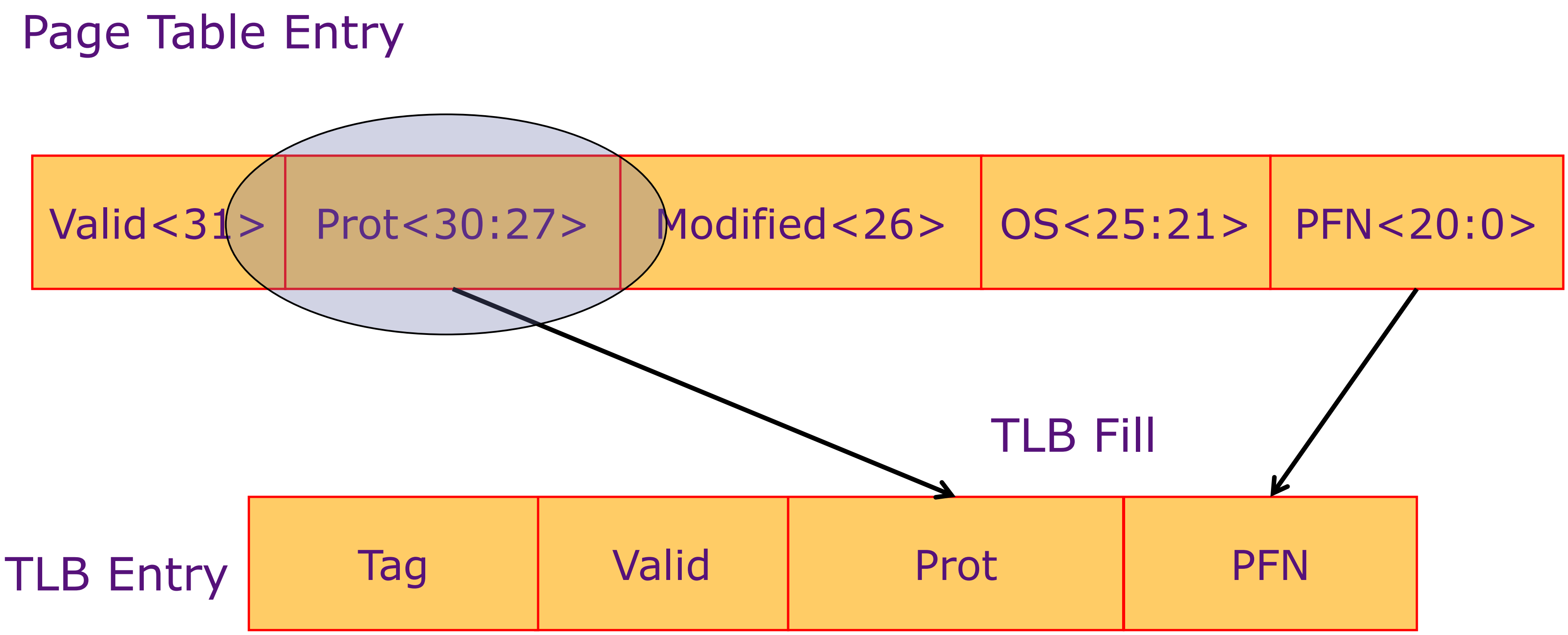

- TLB access checks if protection allows access for current mode
- TLB fills require read/copy page table data -> security sensitive

ISA Extensions to Support OS

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  - Traps (exceptions) to safely transition from user to supervisor mode

Process Mode Switching

Trap, e.g., i/o read() or exception

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Pass arguments;
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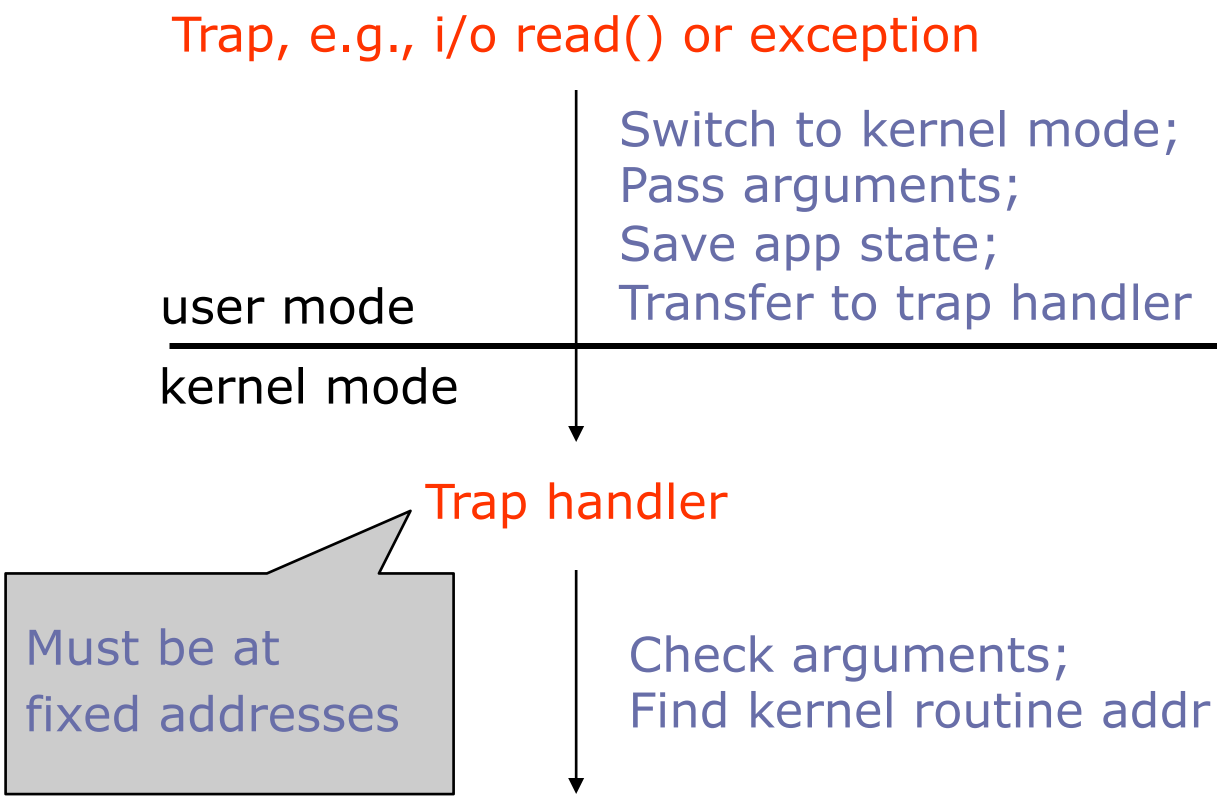

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Why?

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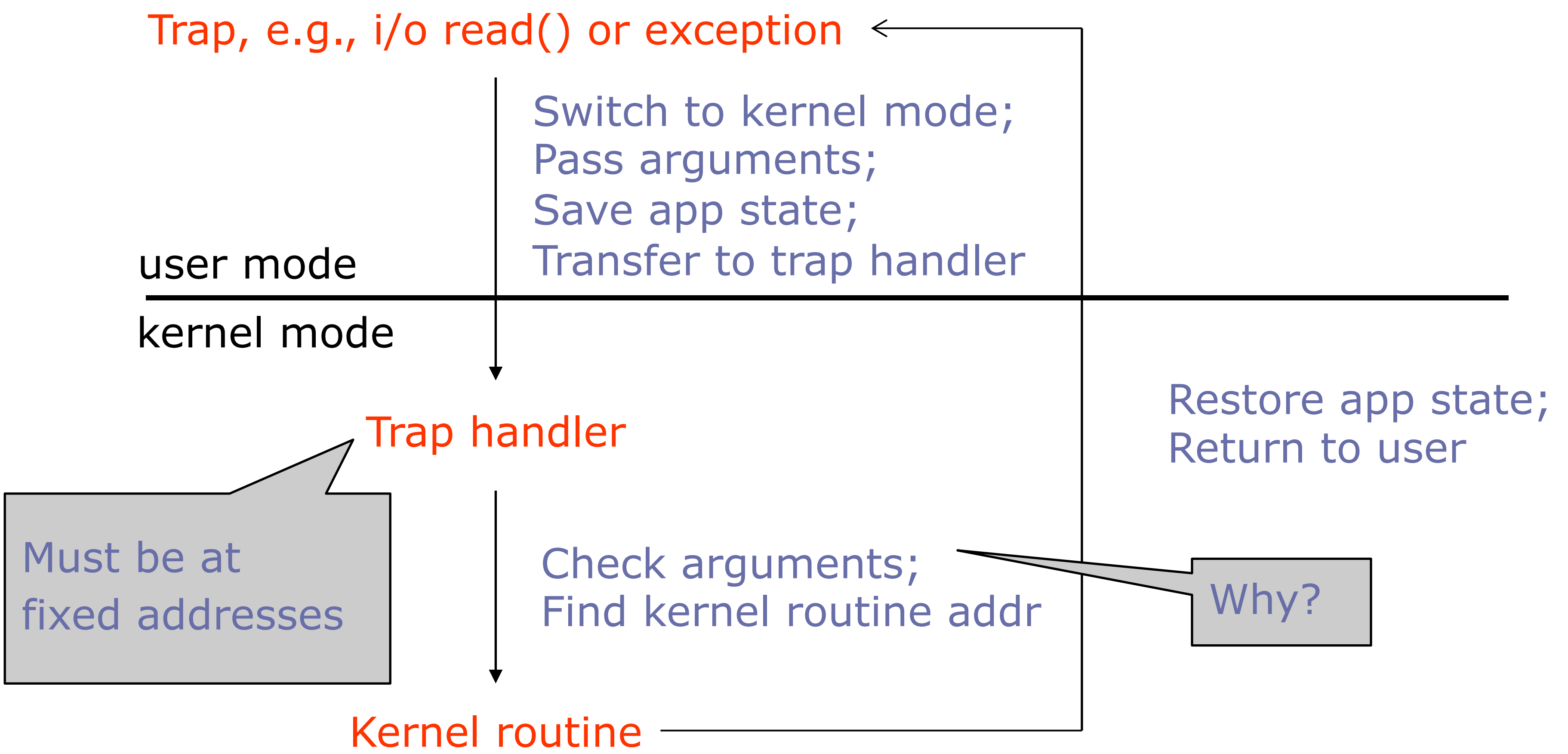

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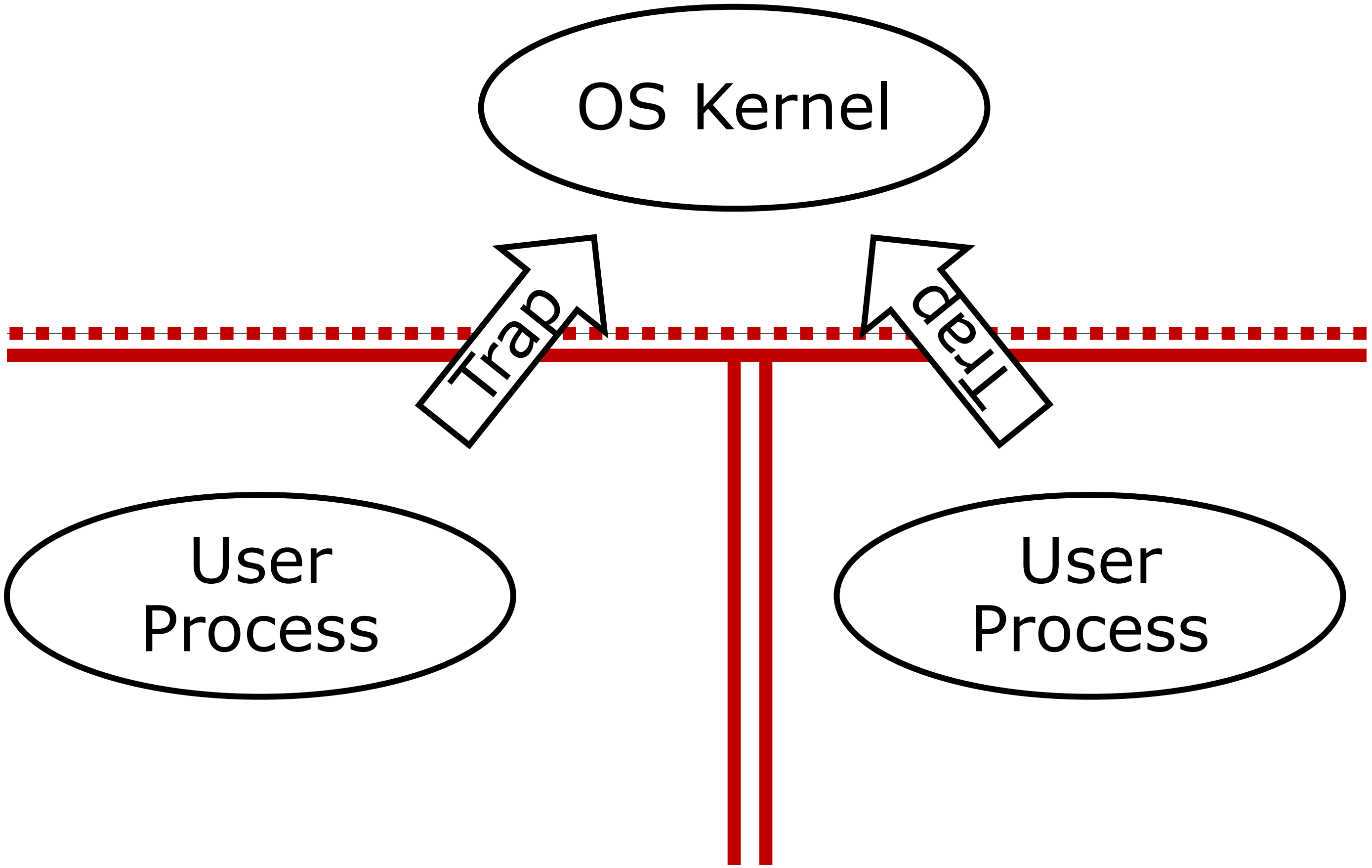

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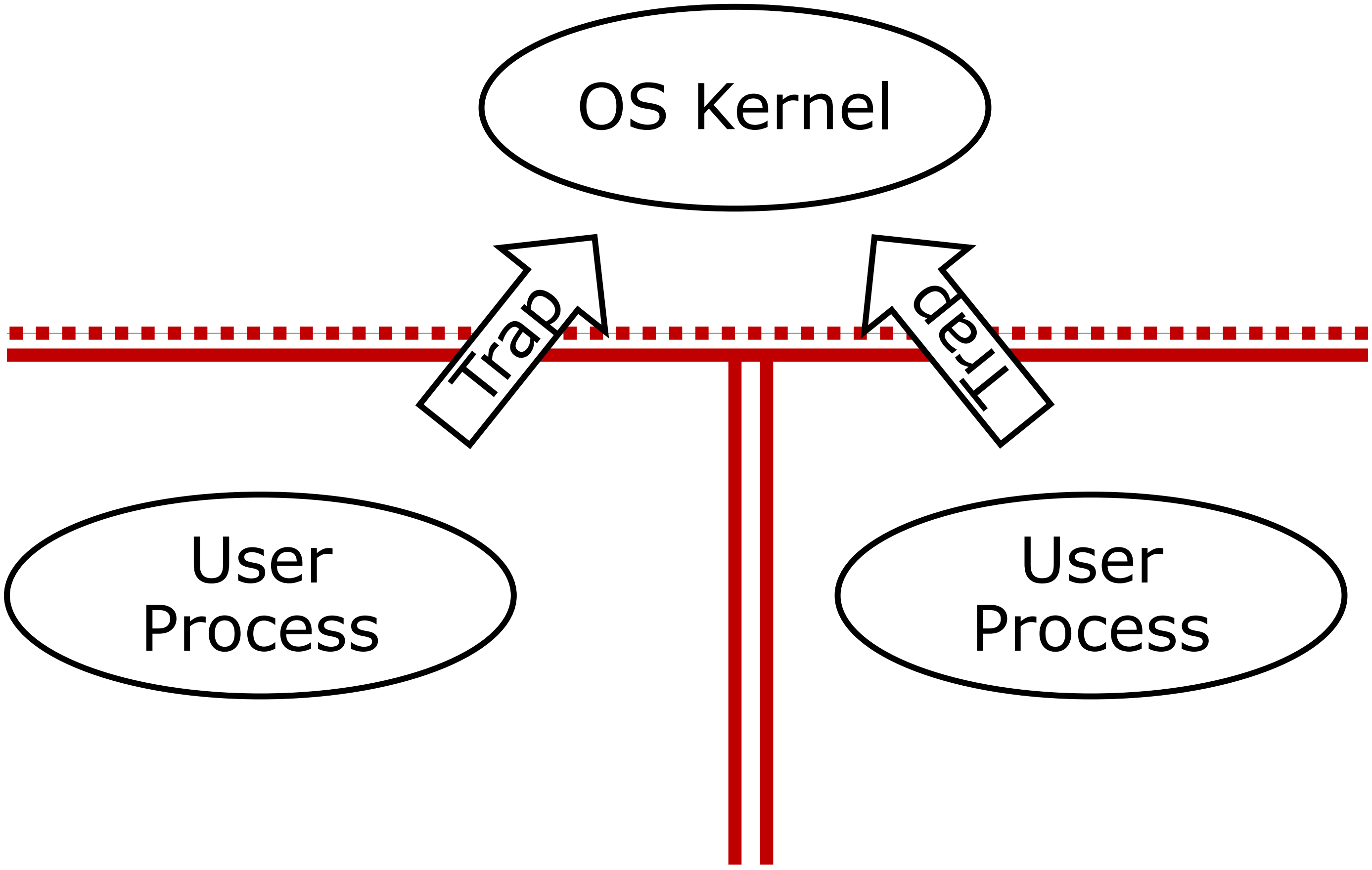

Key idea: Provides a strong abstraction that cannot be escaped

Virtual Machines

- The OS gives a Virtual Machine (VM) to each process
  - Each process believes it runs on its own machine…
  - …but this machine does not exist in physical hardware

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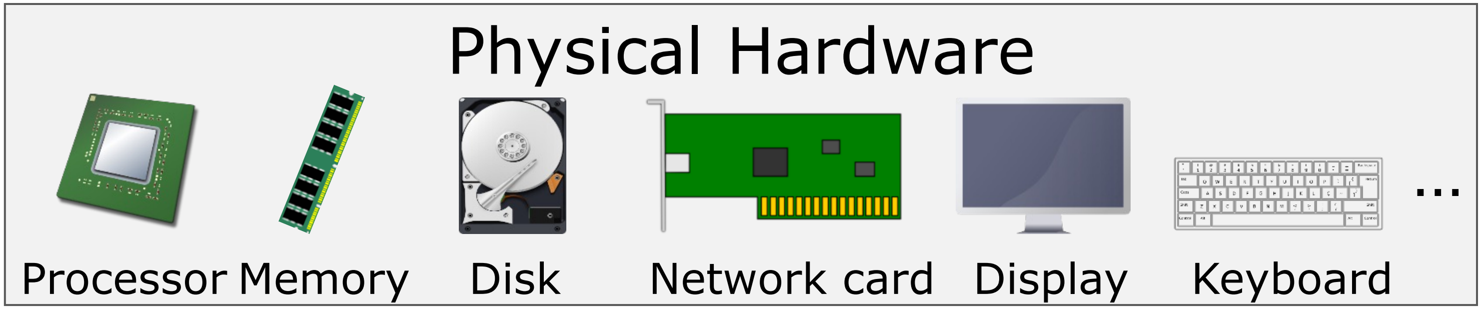

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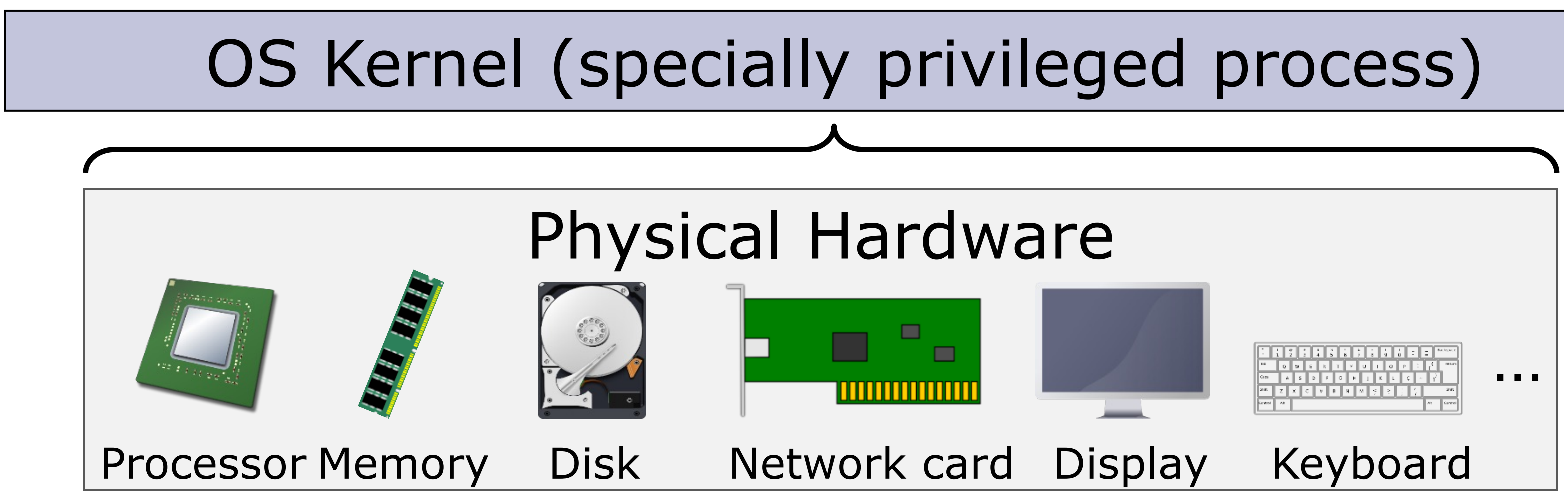

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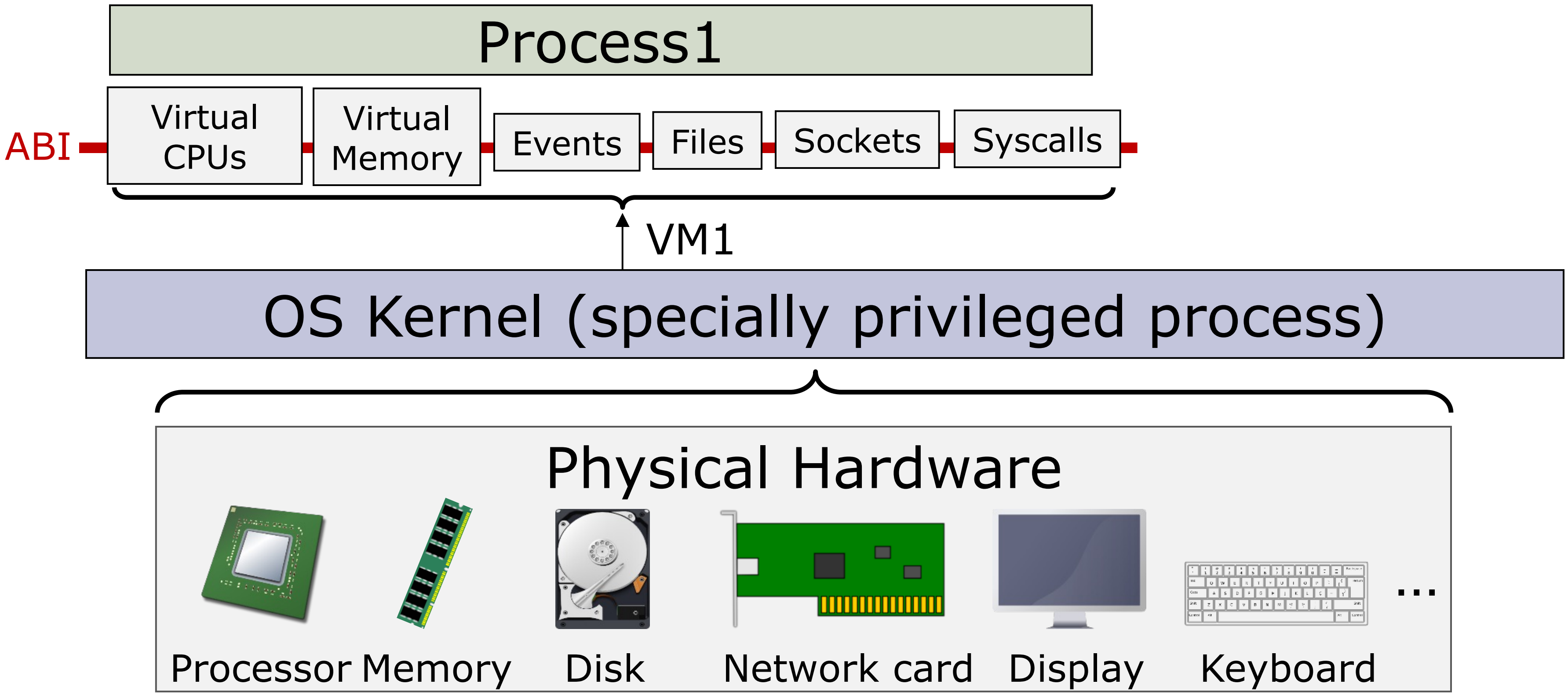

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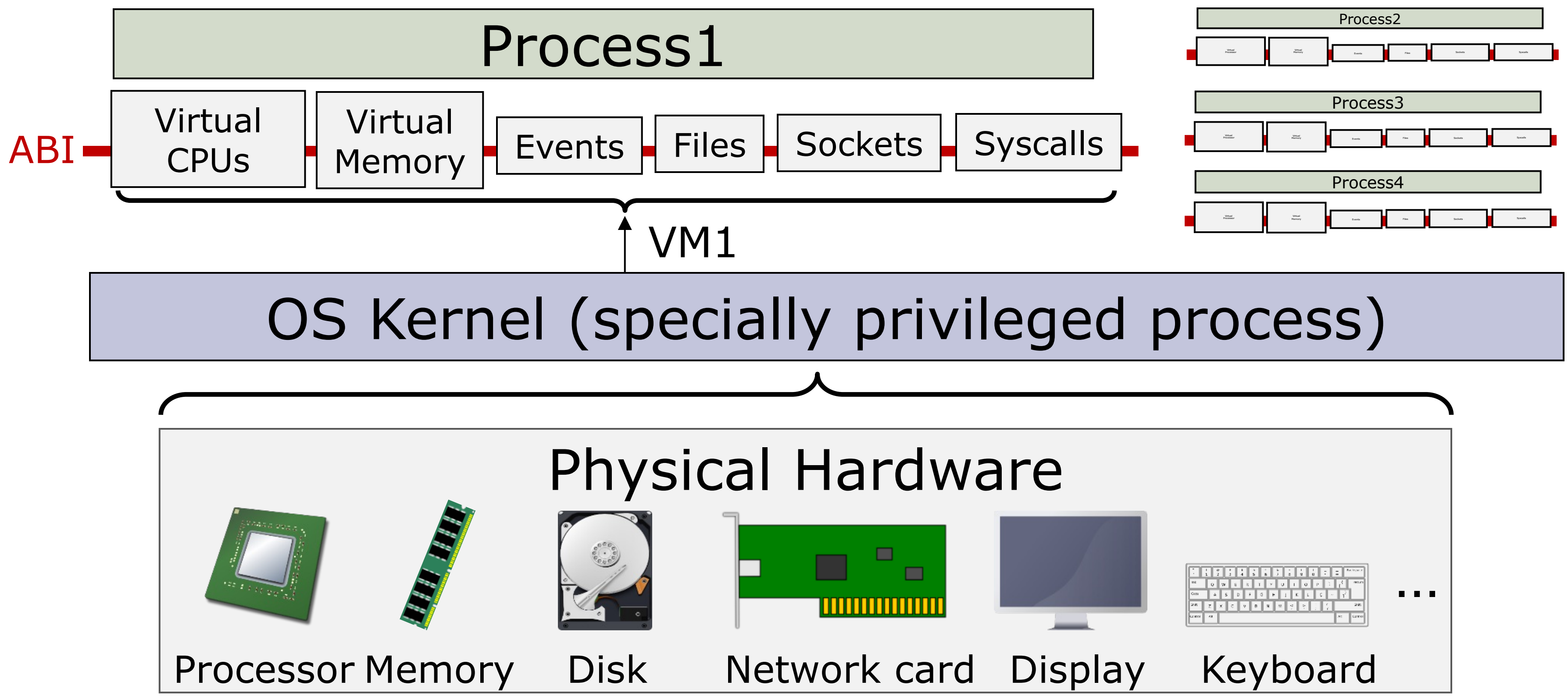
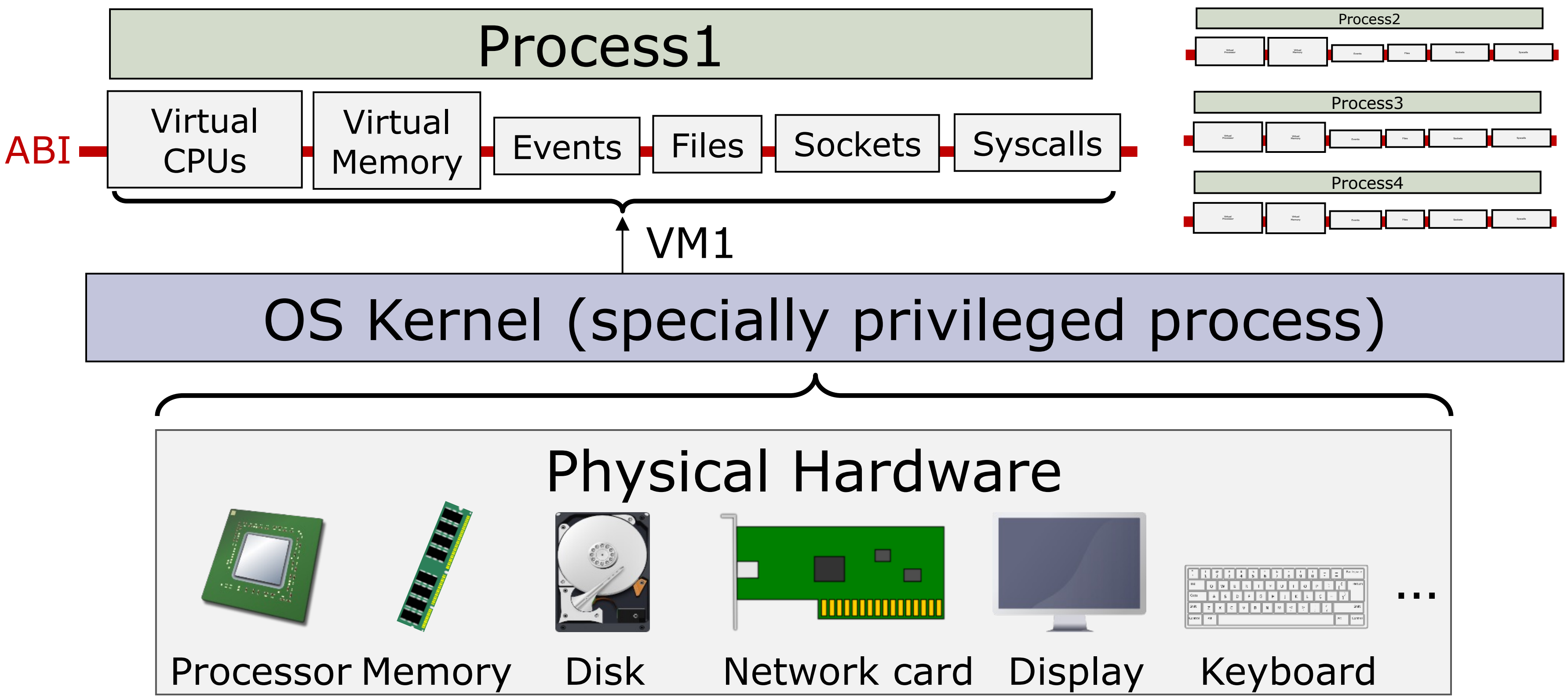


Virtual Machines

- A Virtual Machine (VM) is an emulation of a computer system
  - Very general concept, used beyond operating systems



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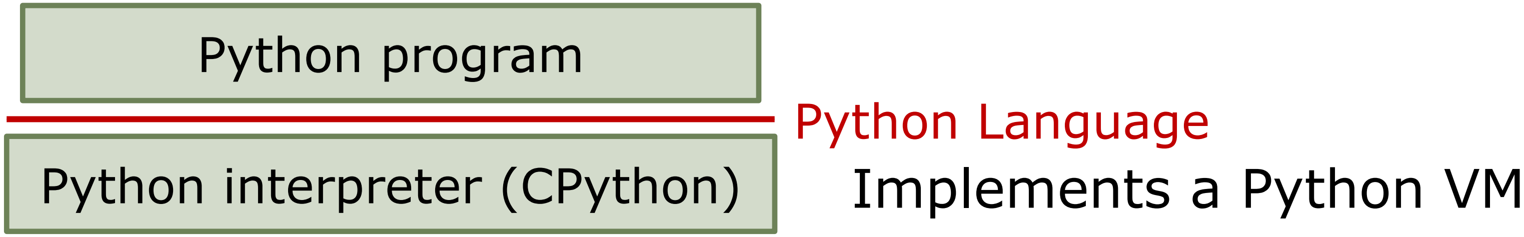

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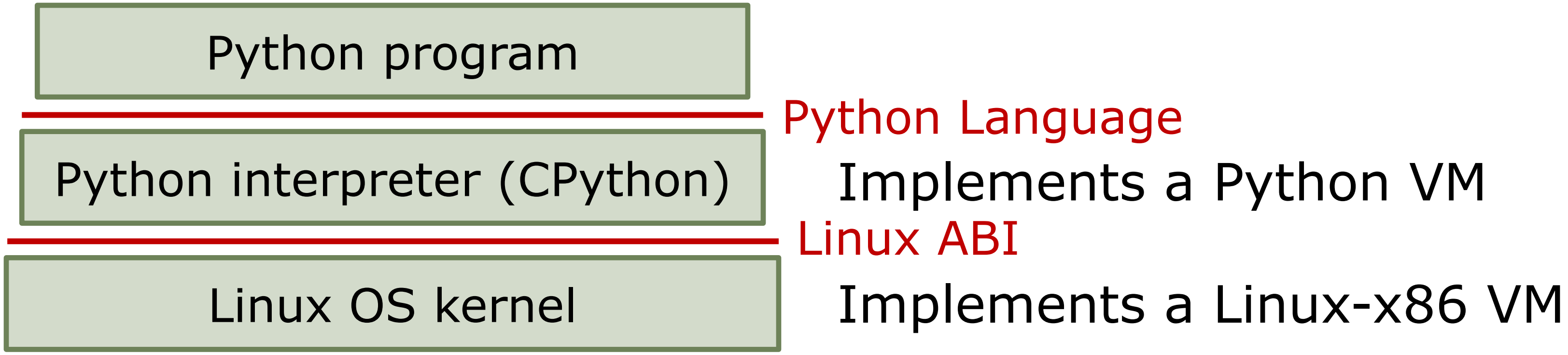

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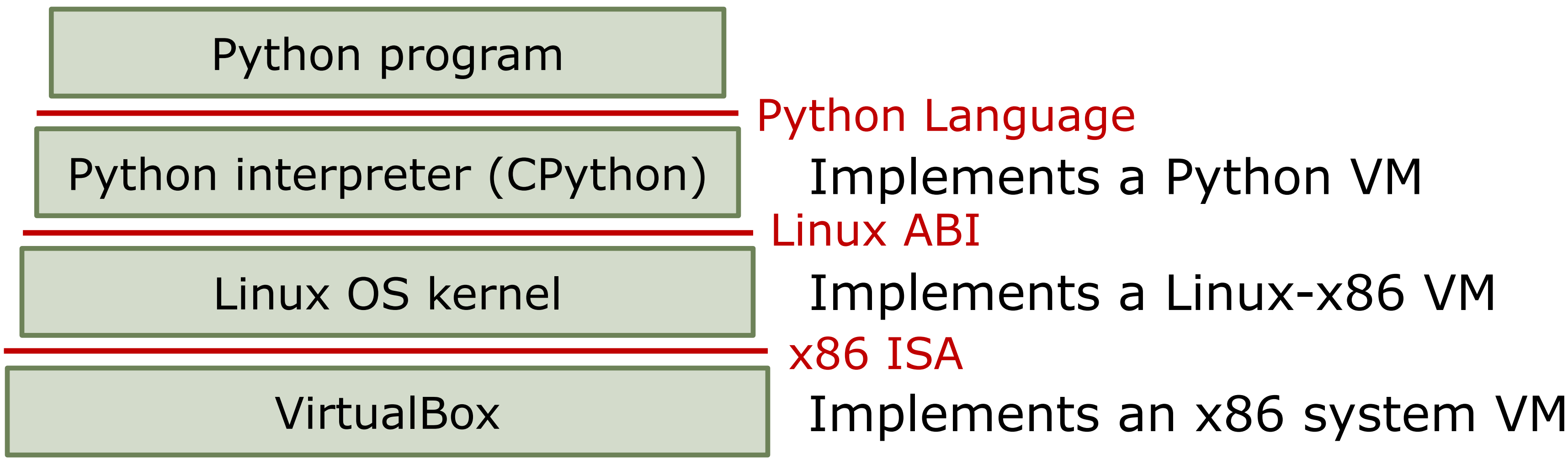

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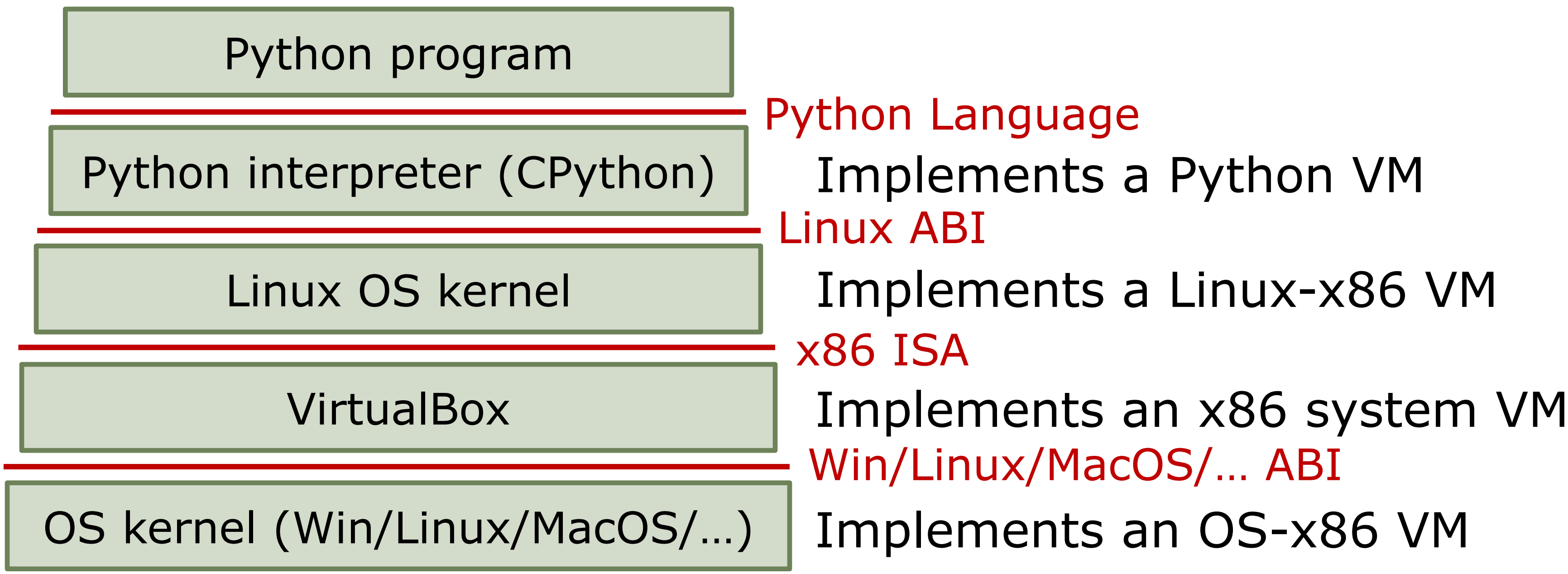

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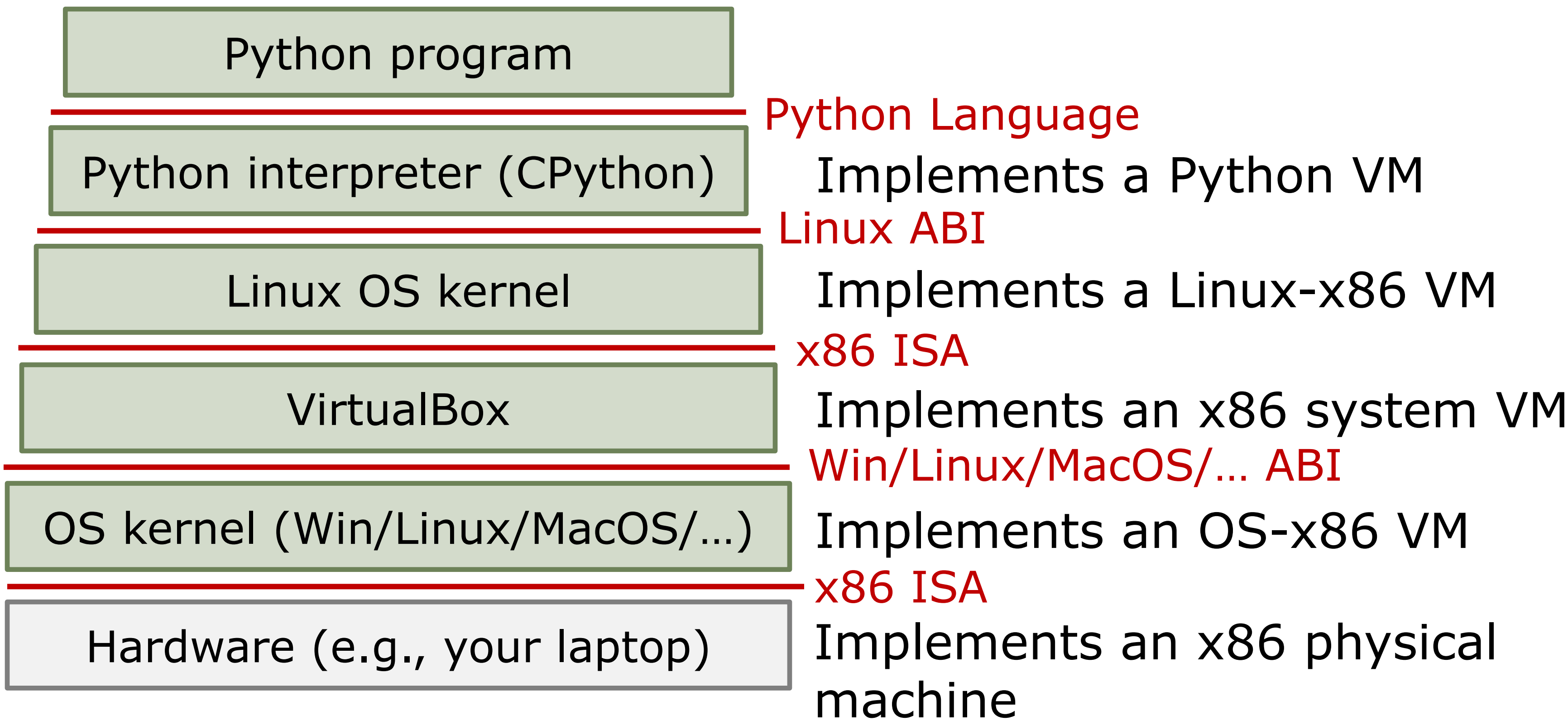

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- We want to support virtual machines with minimal overheads → often need hardware support!

Application-level virtualization

- Programs are usually distributed in a binary format that encodes the program's instructions and initial values of some data segments. These requirements are called the application binary interface (ABI), which can be virtualized

- ABI specifications include
  - Which instructions are available (the ISA)
  - What system calls are possible (I/O, or the *environment*)
  - What state is available at process creation

- Operating system implements the virtual environment
  - At process startup, OS reads the binary program, creates an environment for it, then begins to execute the code, handling traps for I/O calls, emulation, etc.

Full ISA-Level Virtualization

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- Run-time Hardware Emulation
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  - IBM AS/400 to modified PowerPC cores
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- Dynamic Binary Translation *(non-native to native ISA at run time)*
  - Sun's HotSpot Java JIT (just-in-time) compiler
  - Transmeta Crusoe, x86->VLIW code morphing

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  - e.g., IEEE floating-point denormals cause traps in almost all floating-point unit implementations
- Old machine can trap unused opcodes, allows binaries for *new* ISA to run on *old* hardware
  - e.g., Sun SPARC v8 added integer multiply instructions, older v7 CPUs trap and emulate

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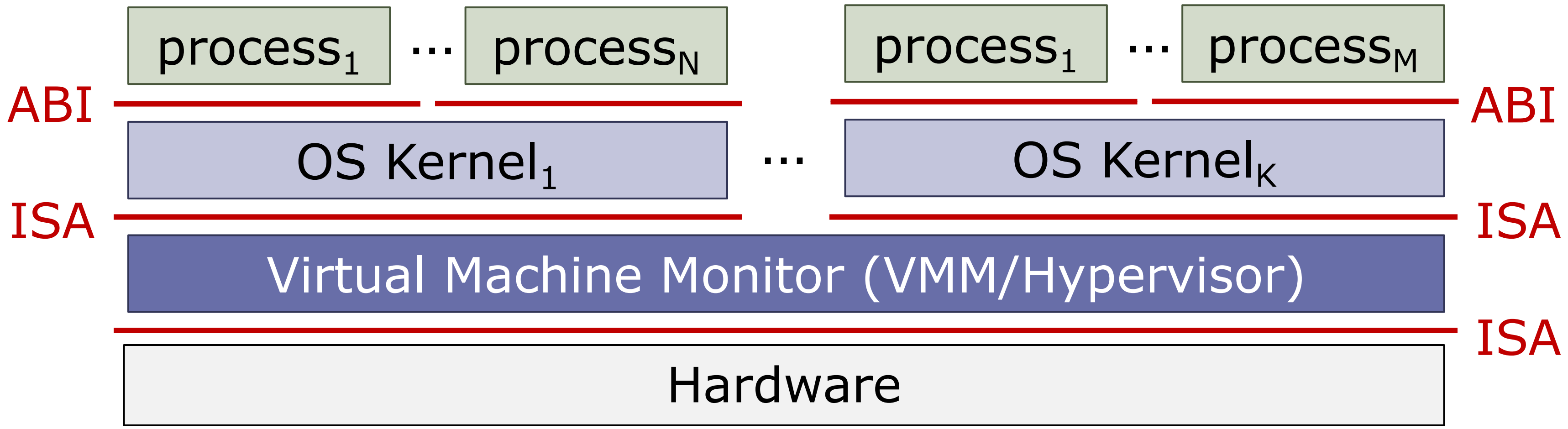
- Allows operating system development without making entire machine unstable or unusable

Supporting Multiple OSs



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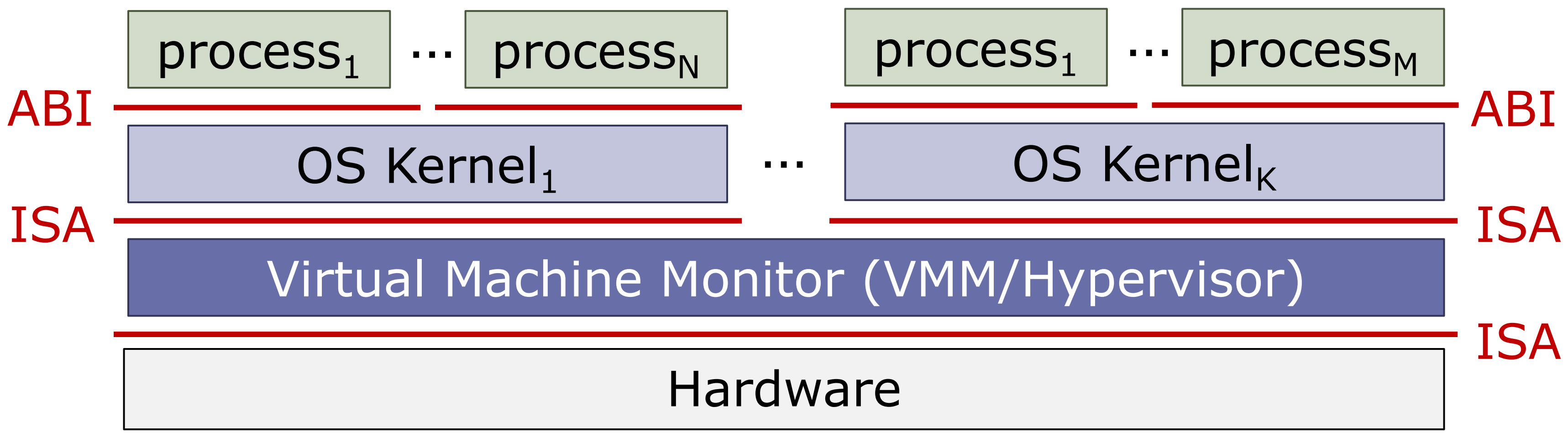
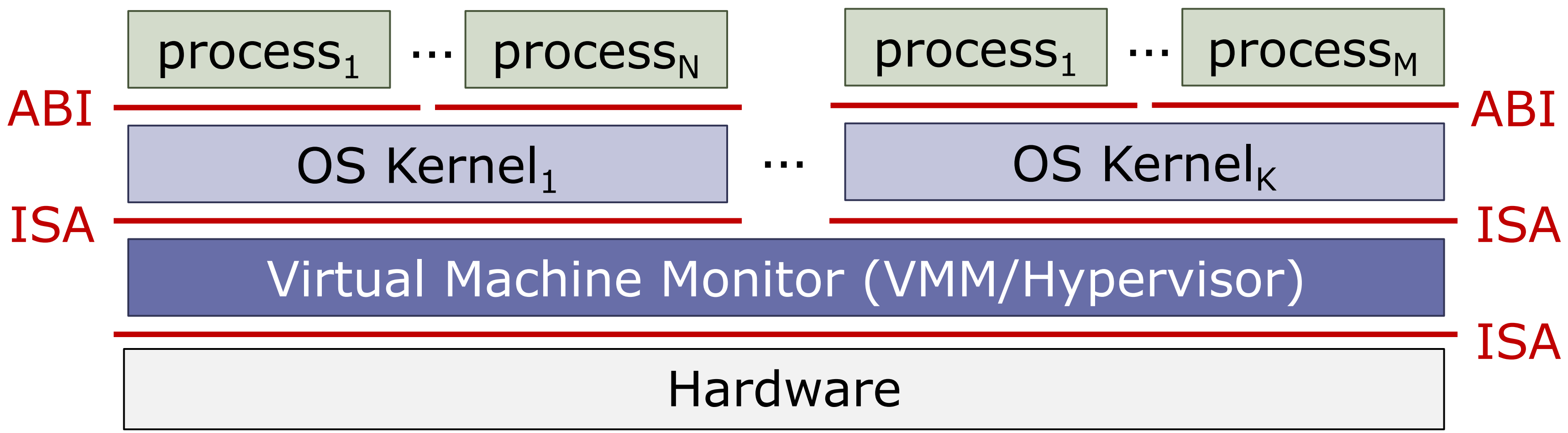


- A VMM (aka Hypervisor) provides a system virtual machine to each OS

Supporting Multiple OSs



- A VMM (aka Hypervisor) provides a system virtual machine to each OS
- VMM can run directly on hardware (as above) or on another OS
  - Precisely, VMM can be implemented against an ISA (as above) or a process-level ABI. Who knows what lays below the interface…

Virtualization Nomenclature

From (Machine we are attempting to execute)

- Guest
- Client
- Foreign ISA

To (Machine that is doing the real execution)

- Host
- Target
- Native ISA

Virtual Machine Requirements
[Popek and Goldberg, 1974]

- Equivalence/Fidelity: A program running on the VMM should exhibit a behavior essentially identical to that demonstrated when running on an equivalent machine directly.

- Resource control/Safety: The VMM must be in complete control of the virtualized resources.

- Efficiency/Performance: A statistically dominant fraction of machine instructions must be executed without VMM intervention.

Virtual Machine Requirements
[Popek and Goldberg, 1974]

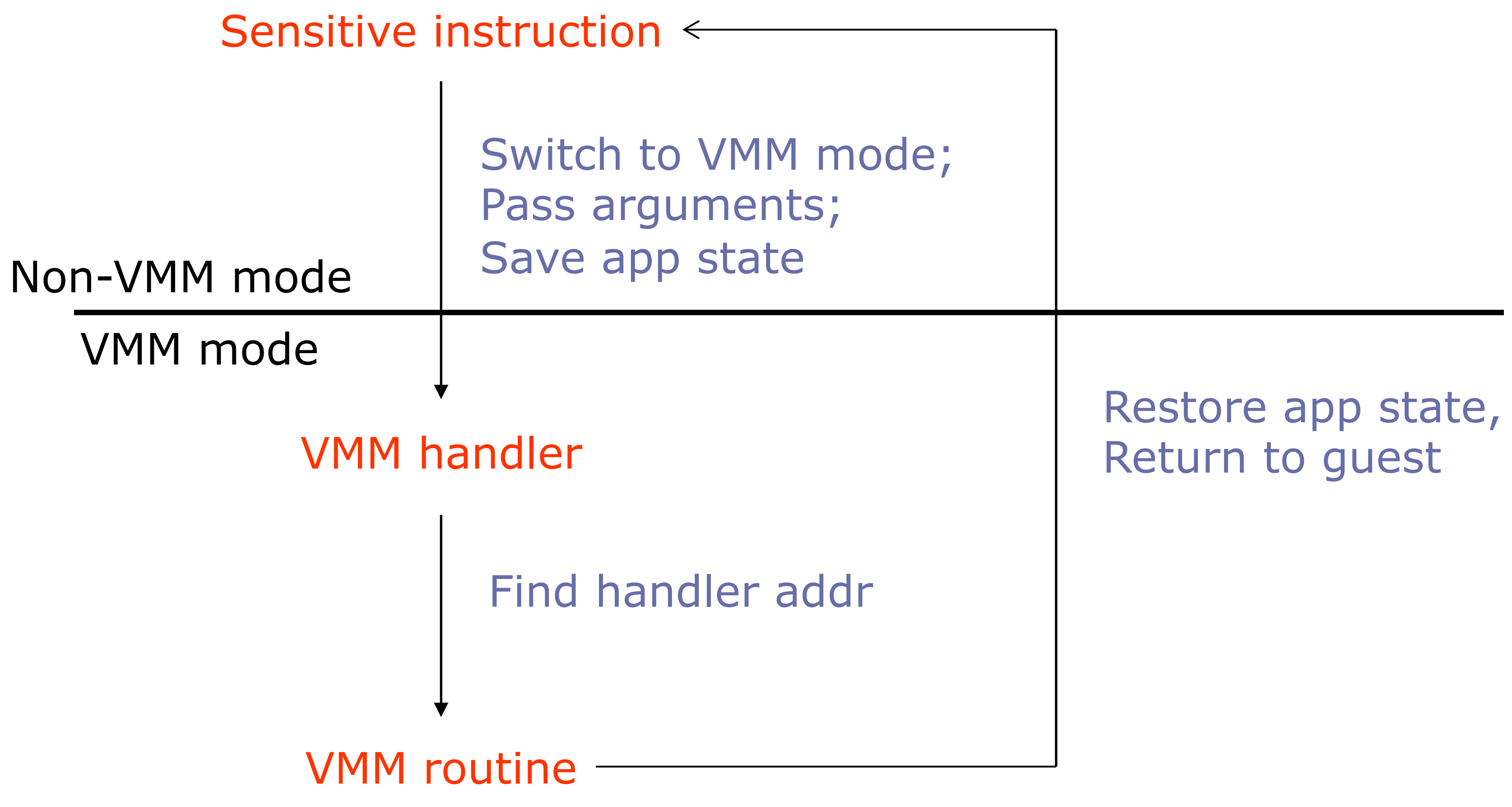
Classification of instructions into 3 groups:

- Privileged instructions: Instructions that trap if the processor is in user mode and do not trap if it is in a more privileged mode.
- Control-sensitive instructions: Instructions that attempt to change the configuration of resources in the system.
- Behavior-sensitive instructions: Those whose behavior depends on the configuration of resources, e.g., mode

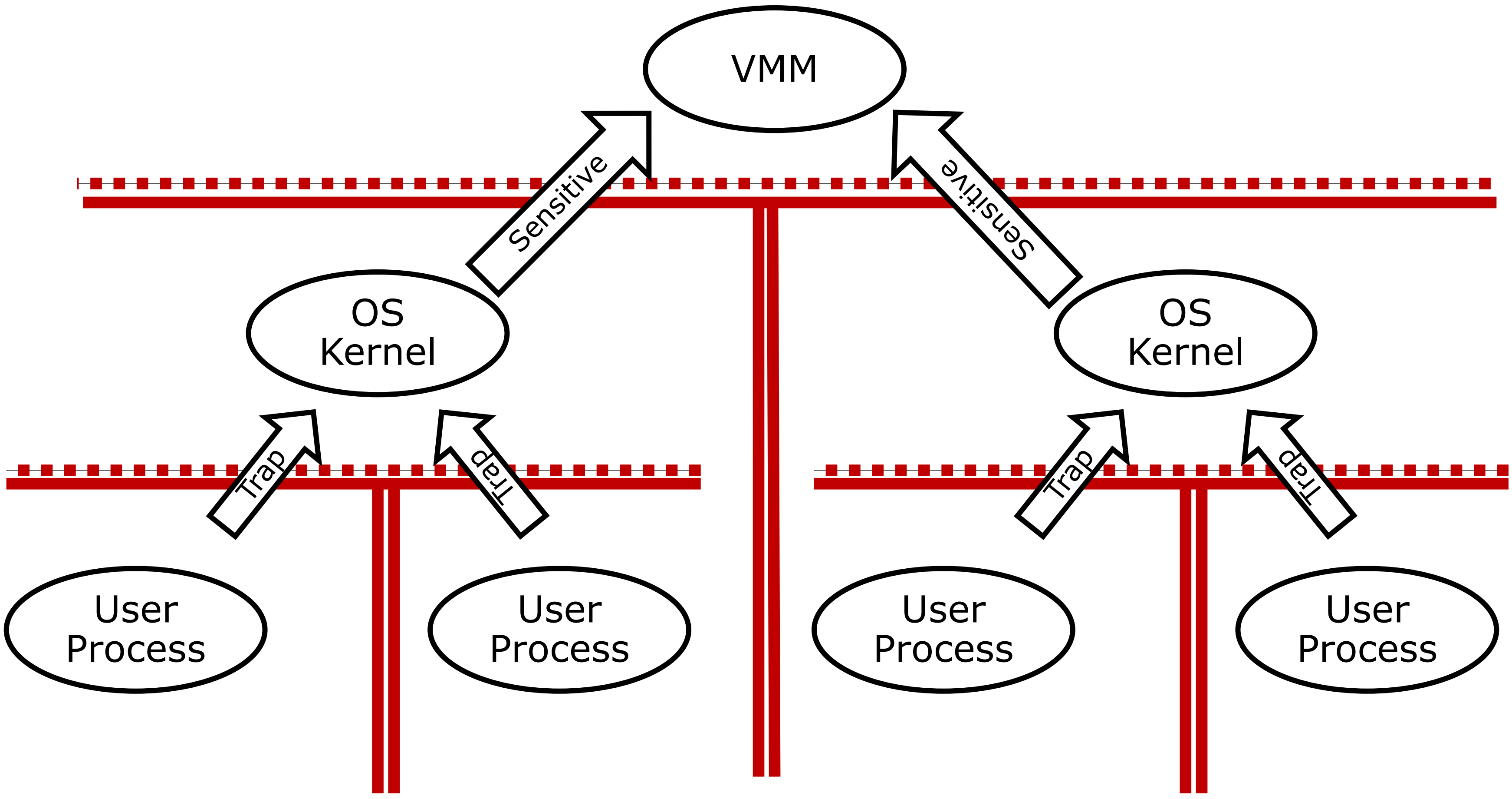
Building an *effective* VMM for an architecture is possible if the set of sensitive instructions is a subset of the set of privileged instructions.

Run OS code using the *trap-and-emulate* strategy.

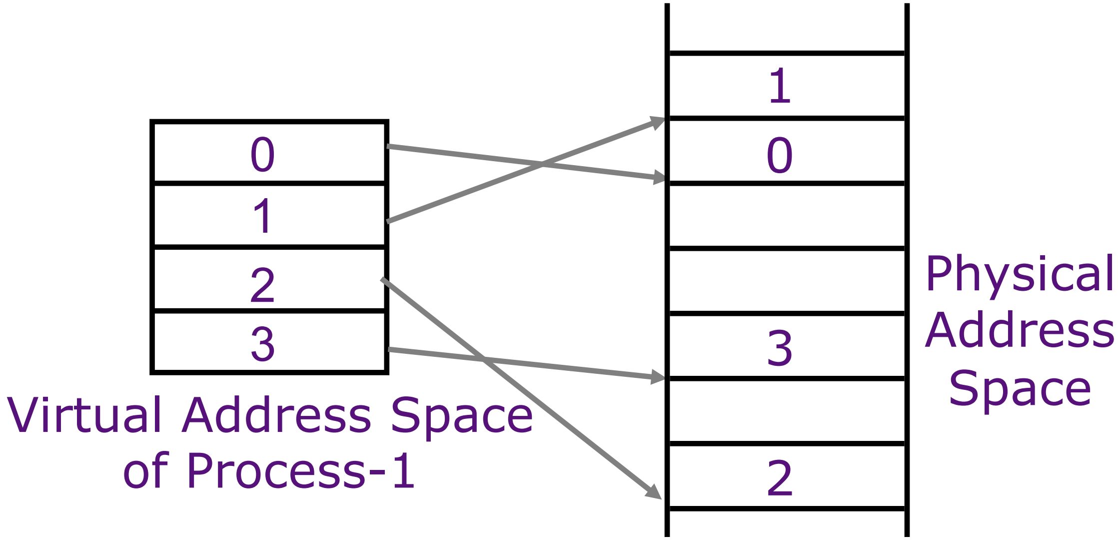
Sensitive instruction handling



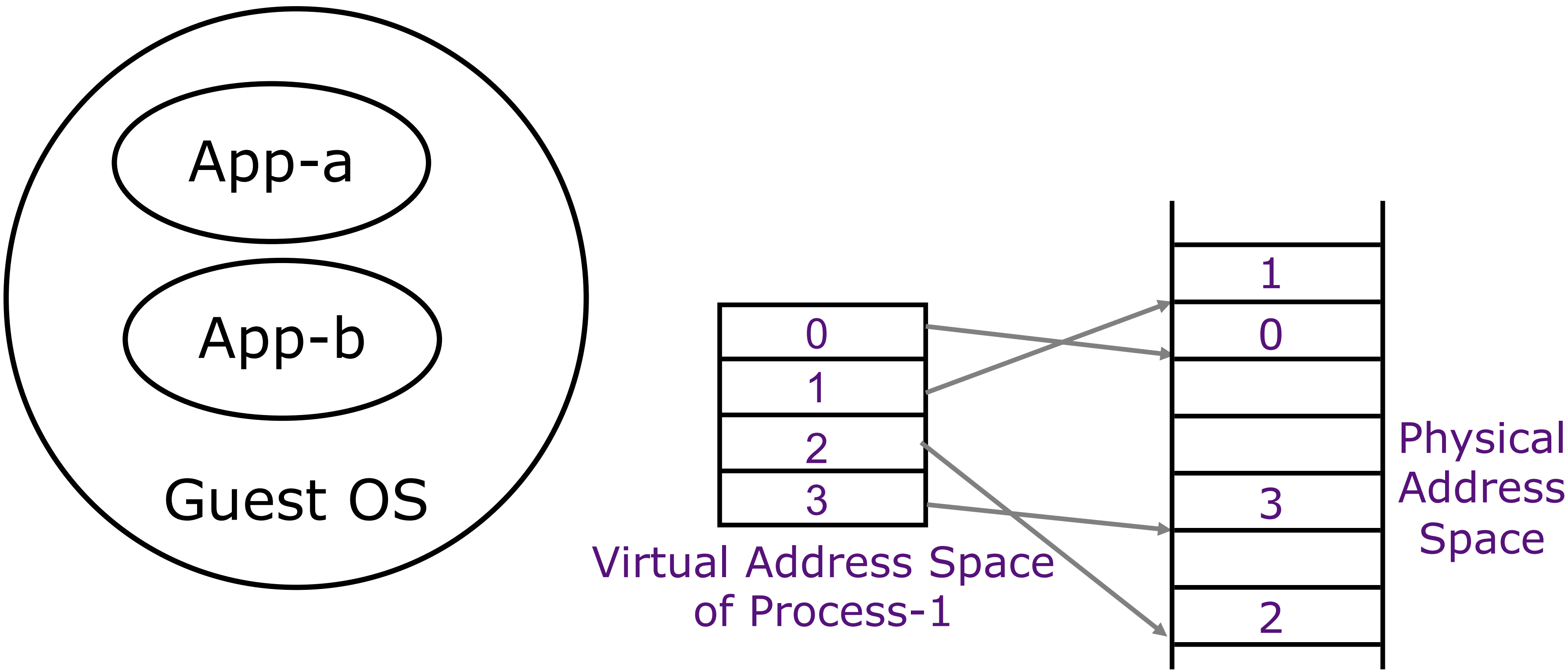
Protection – Multiple OS



Virtual Memory in VMs



Virtual Memory in VMs



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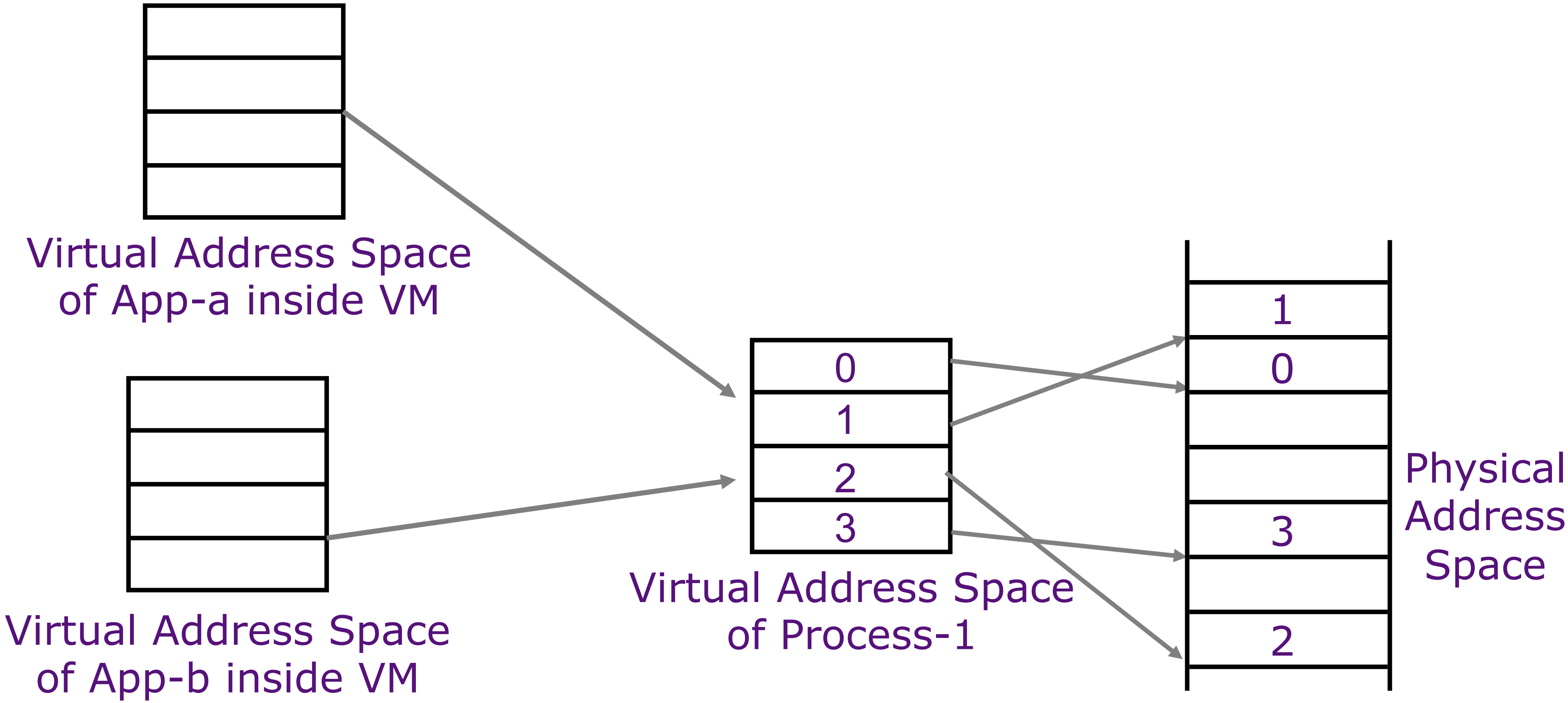
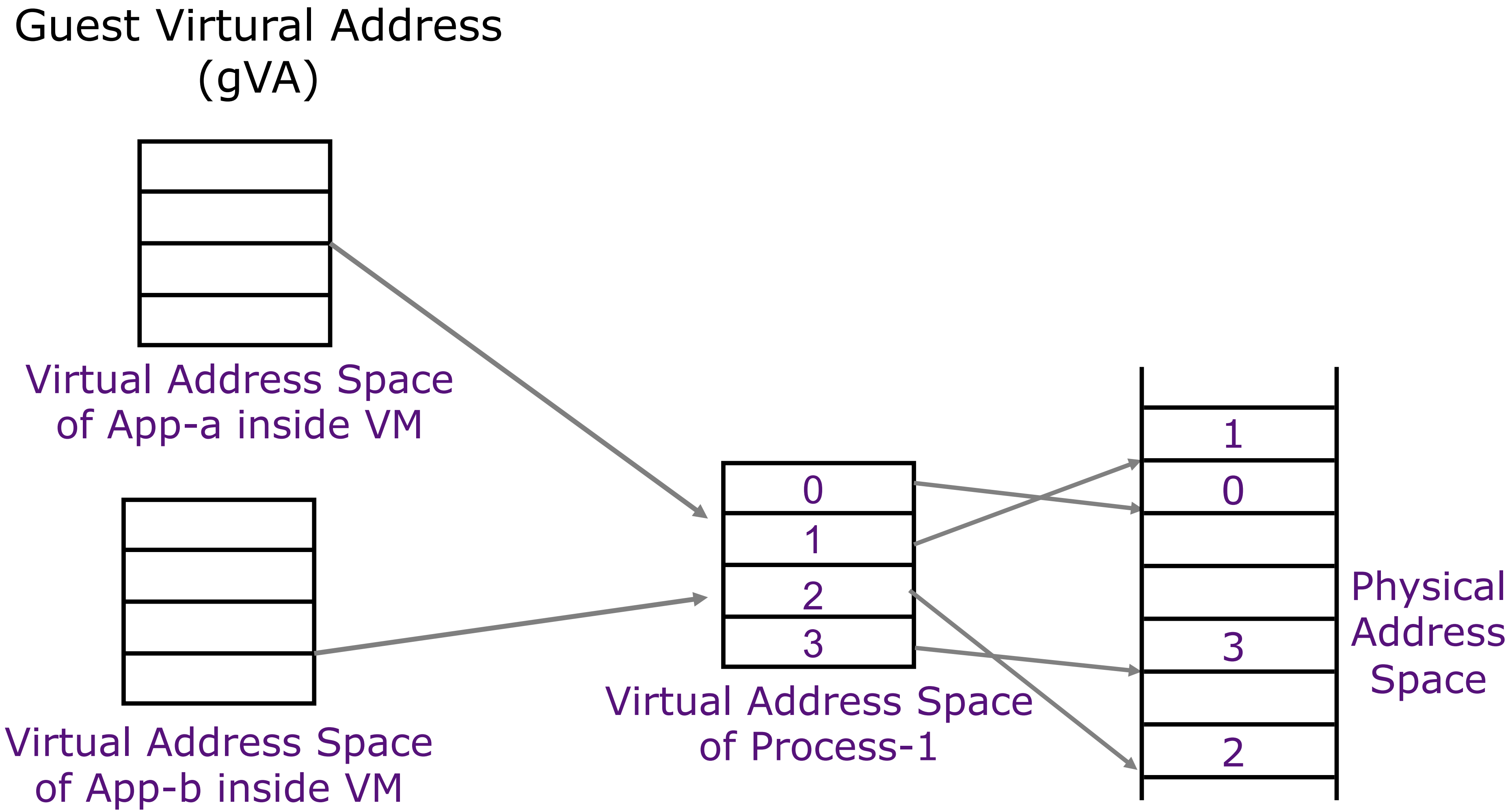
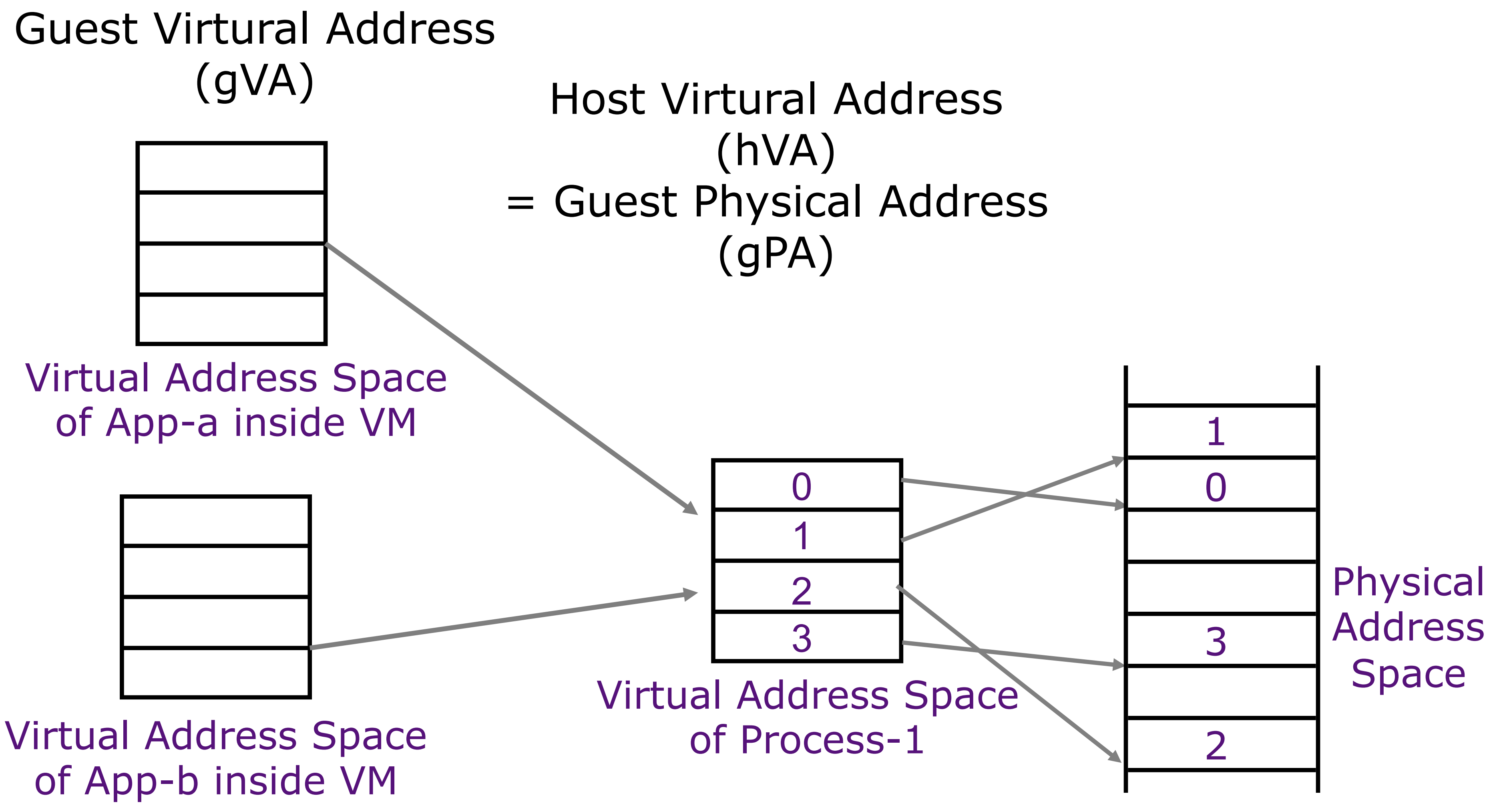


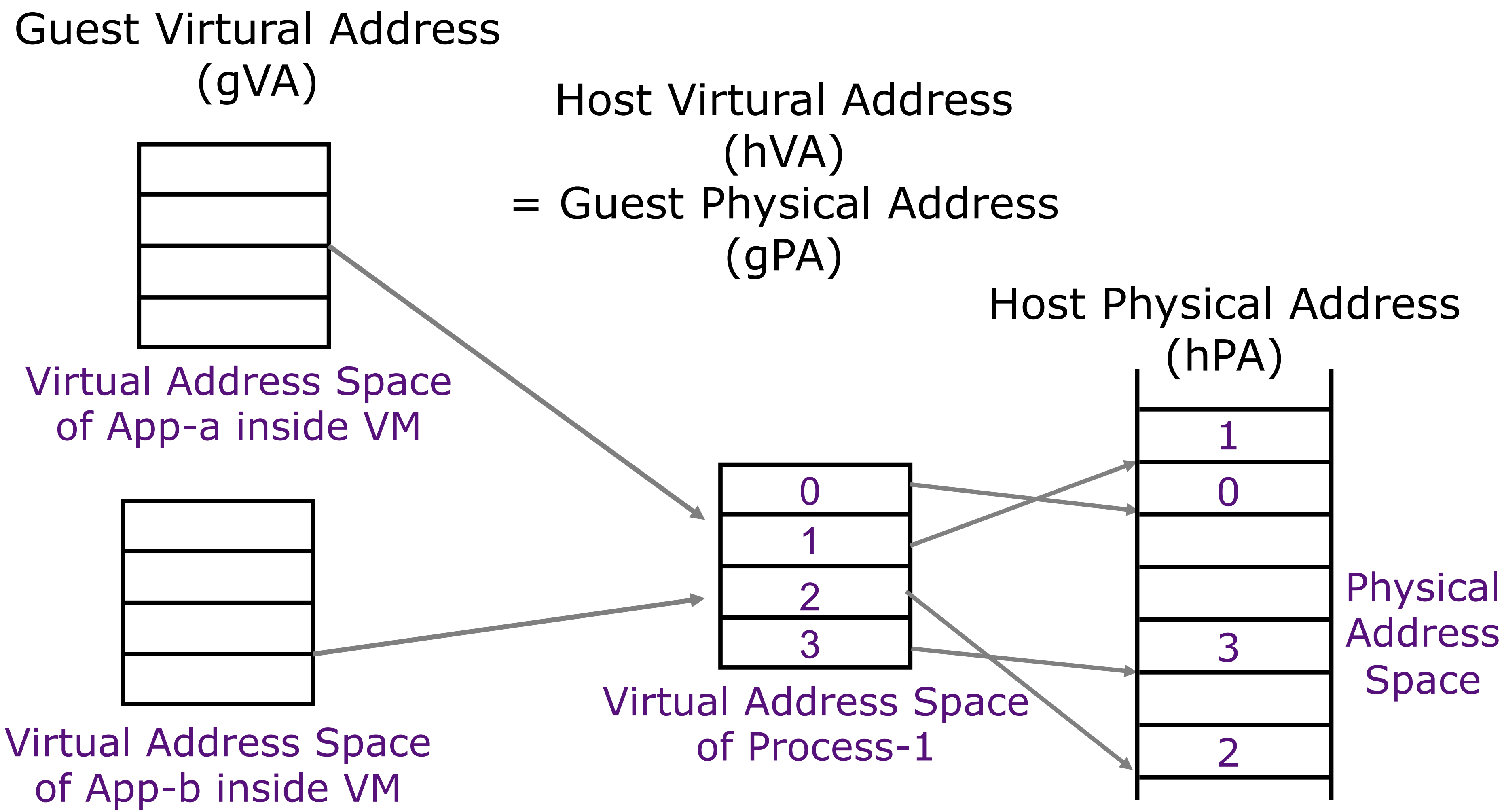
Virtual Memory in VMs



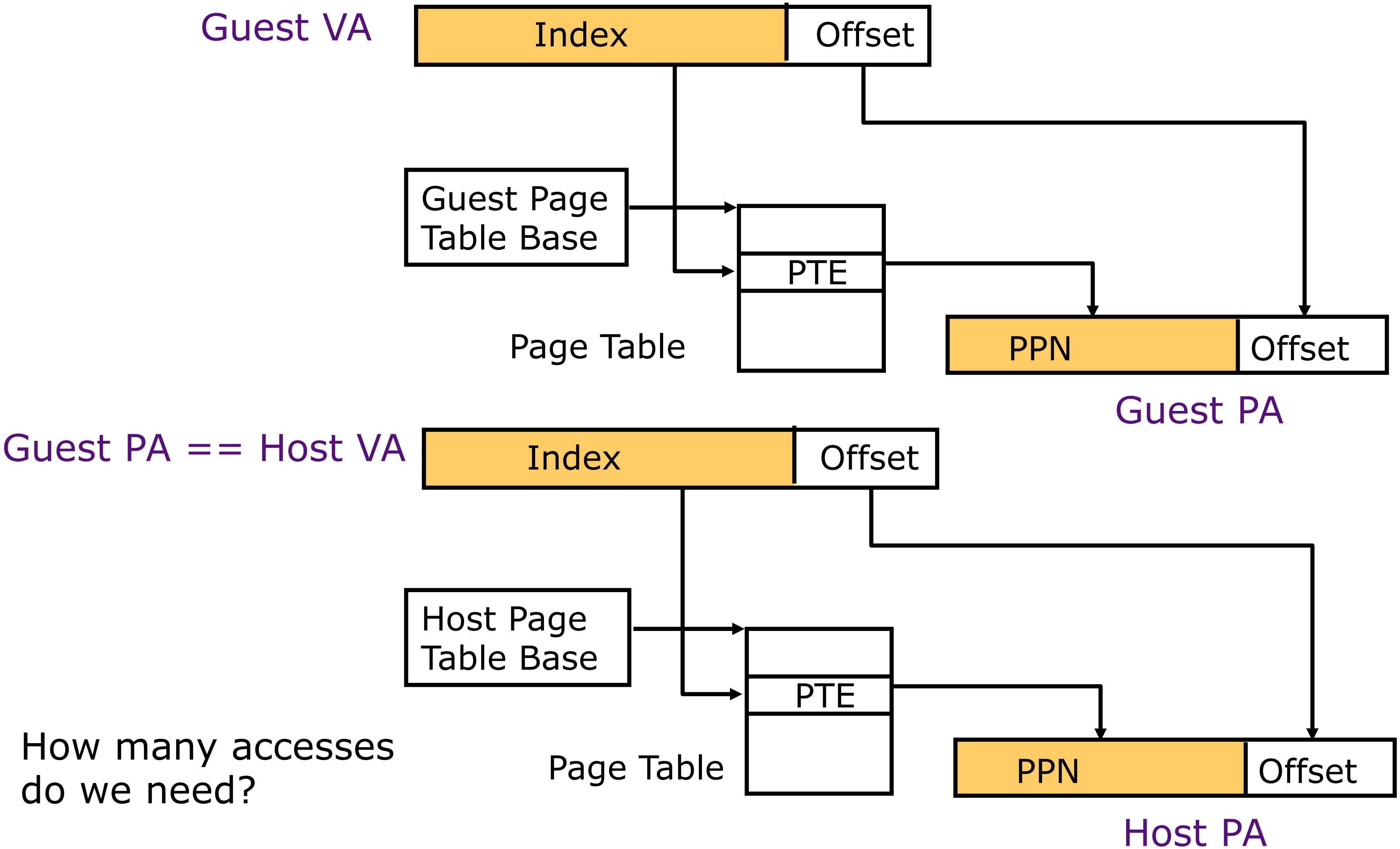
Virtual Memory in VMs



Virtual Memory in VMs

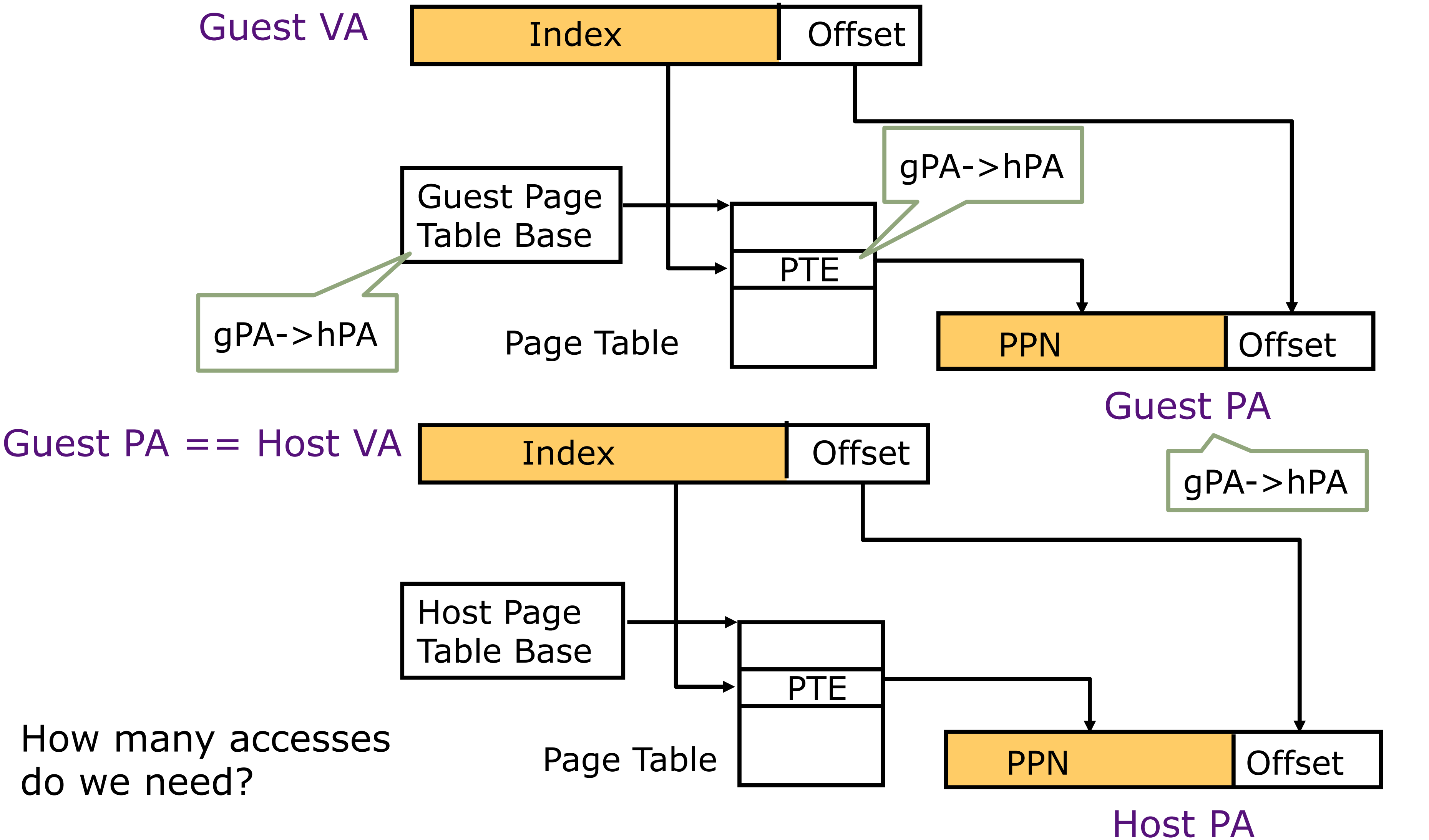


Nested Page Tables



How many accesses do we need?

Nested Page Tables



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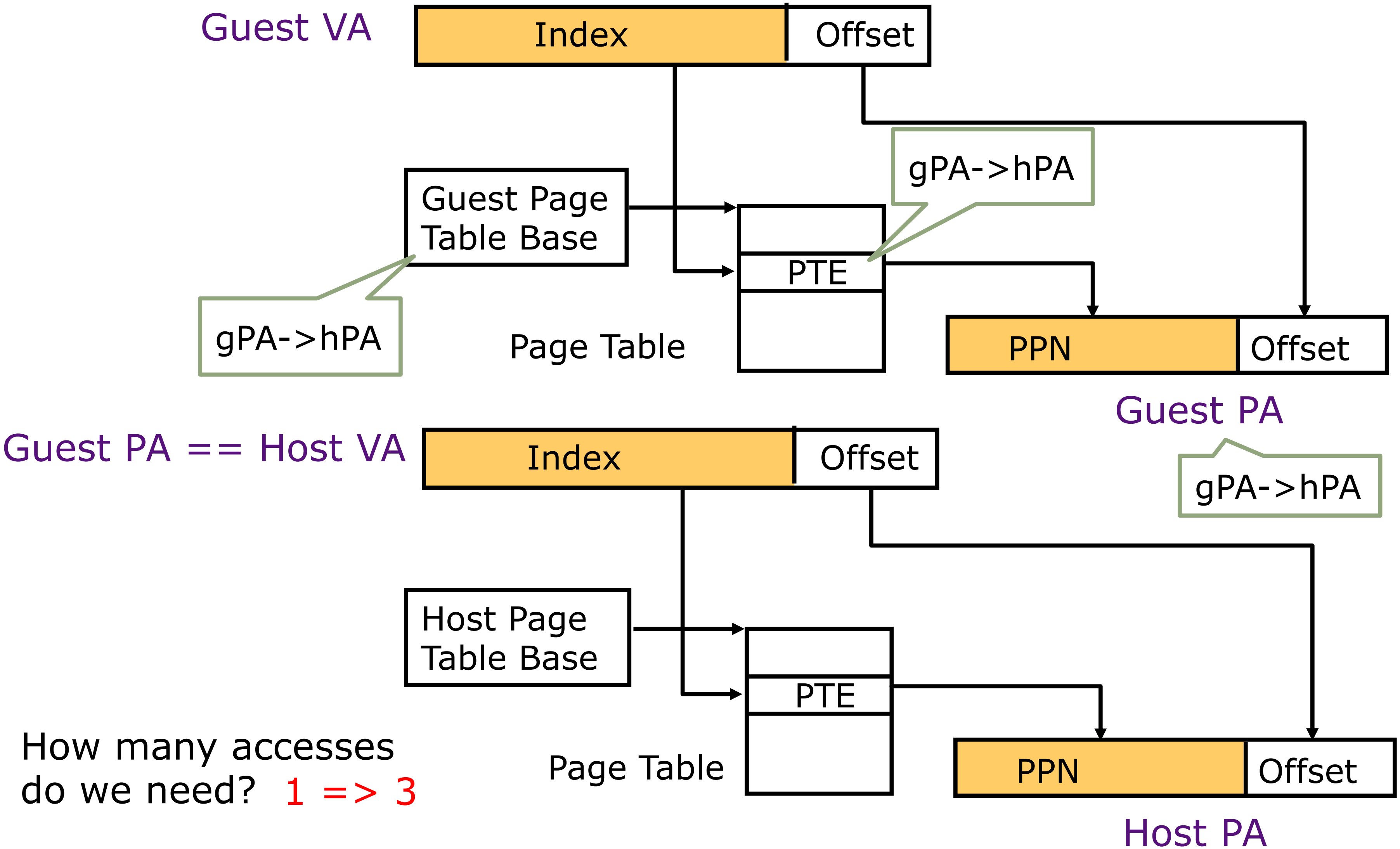
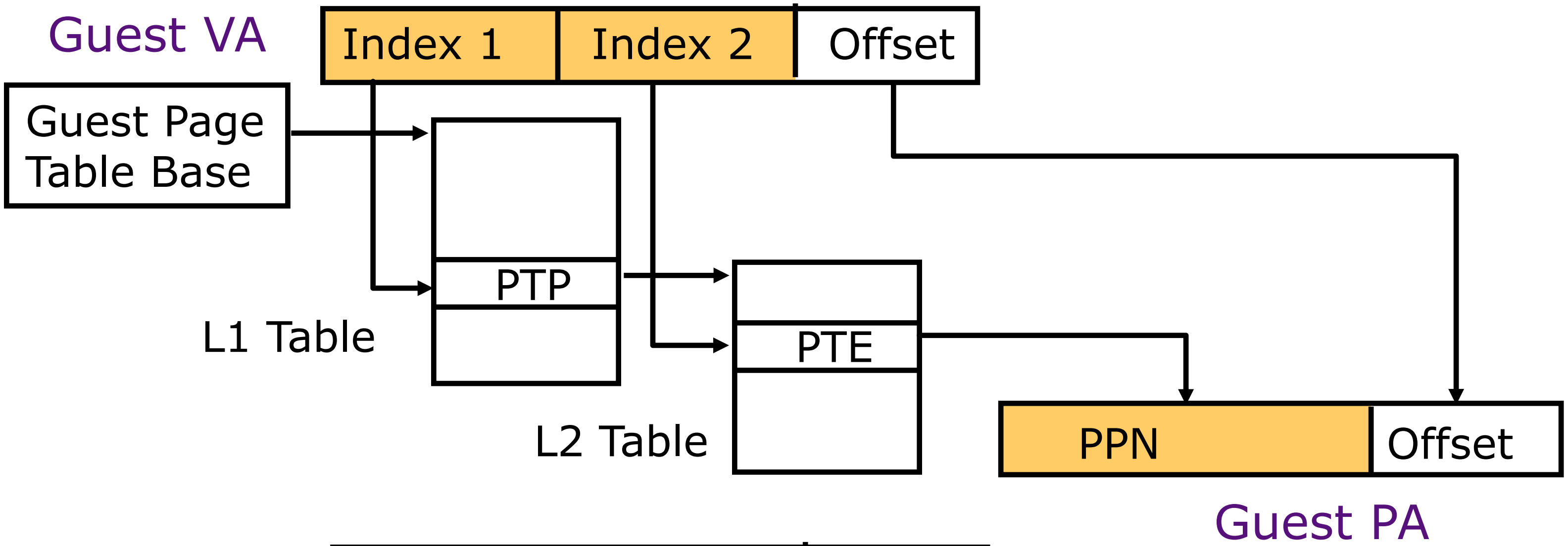
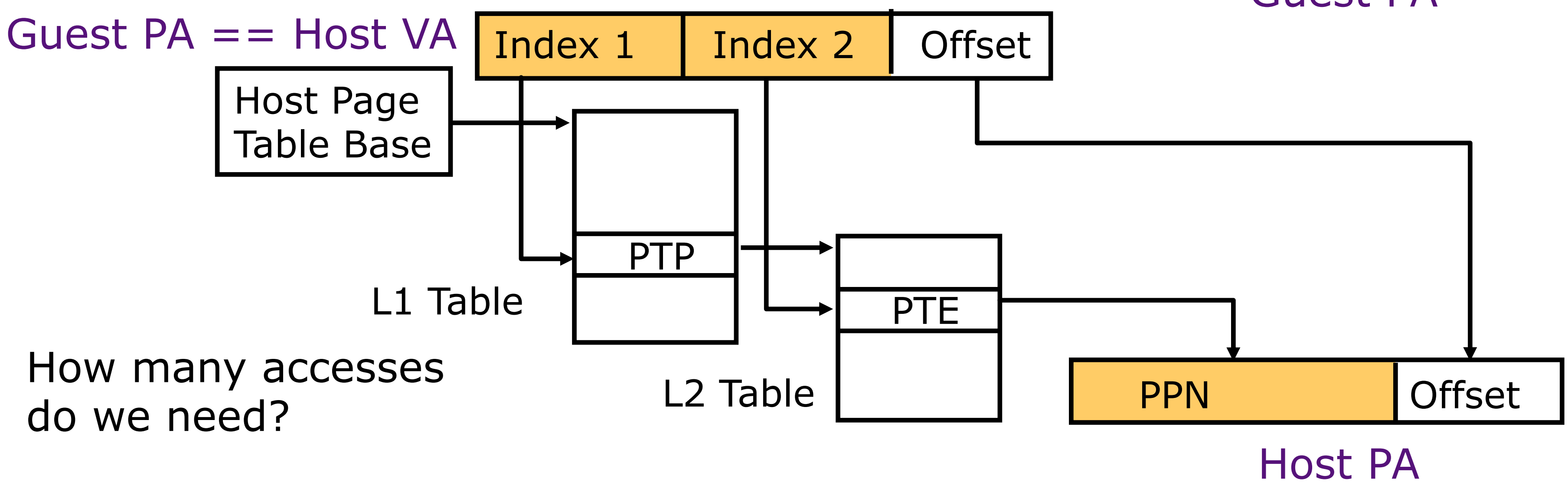


How many accesses do we need? 1 => 3

Nested Page Tables (Hierarchical)





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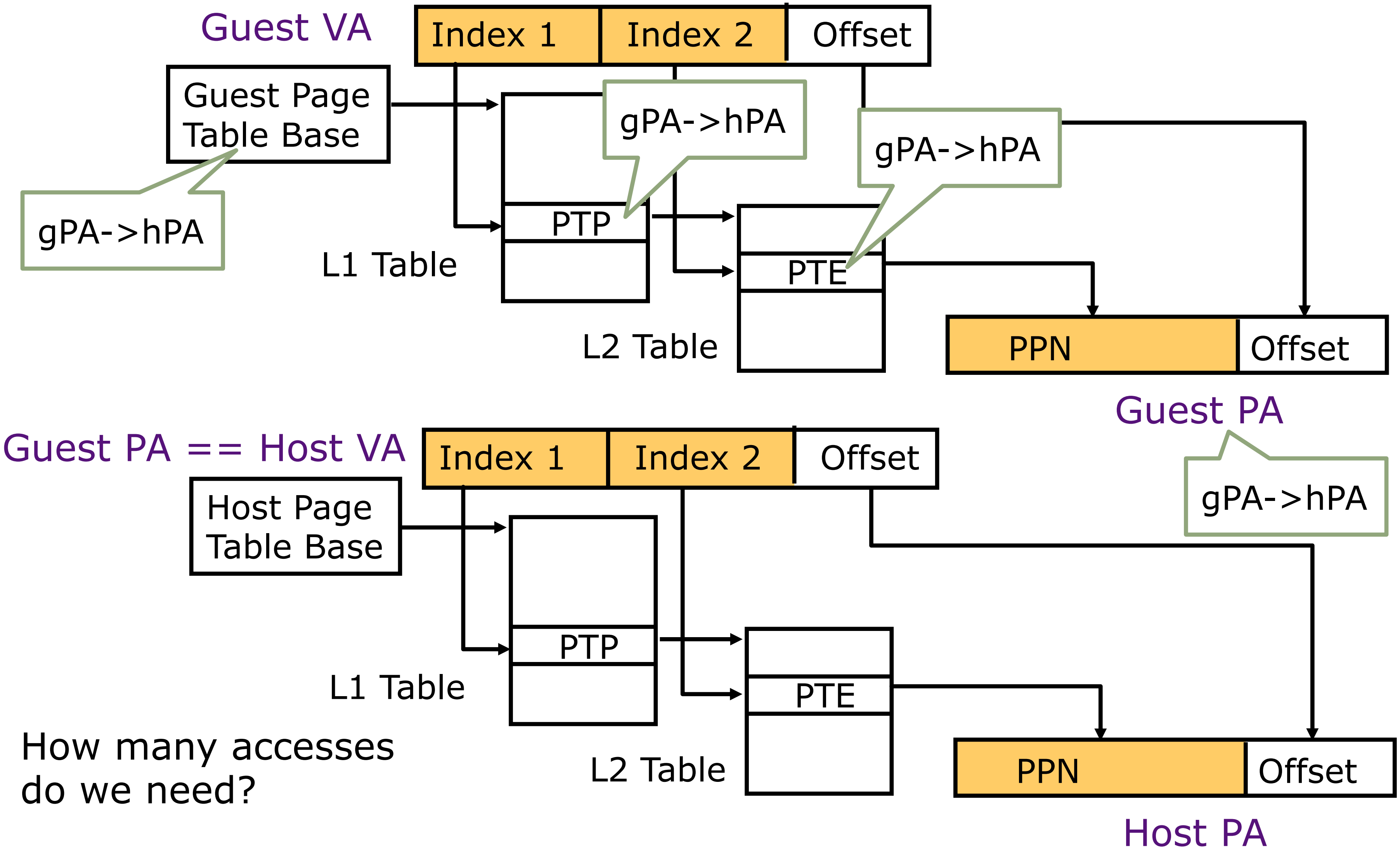

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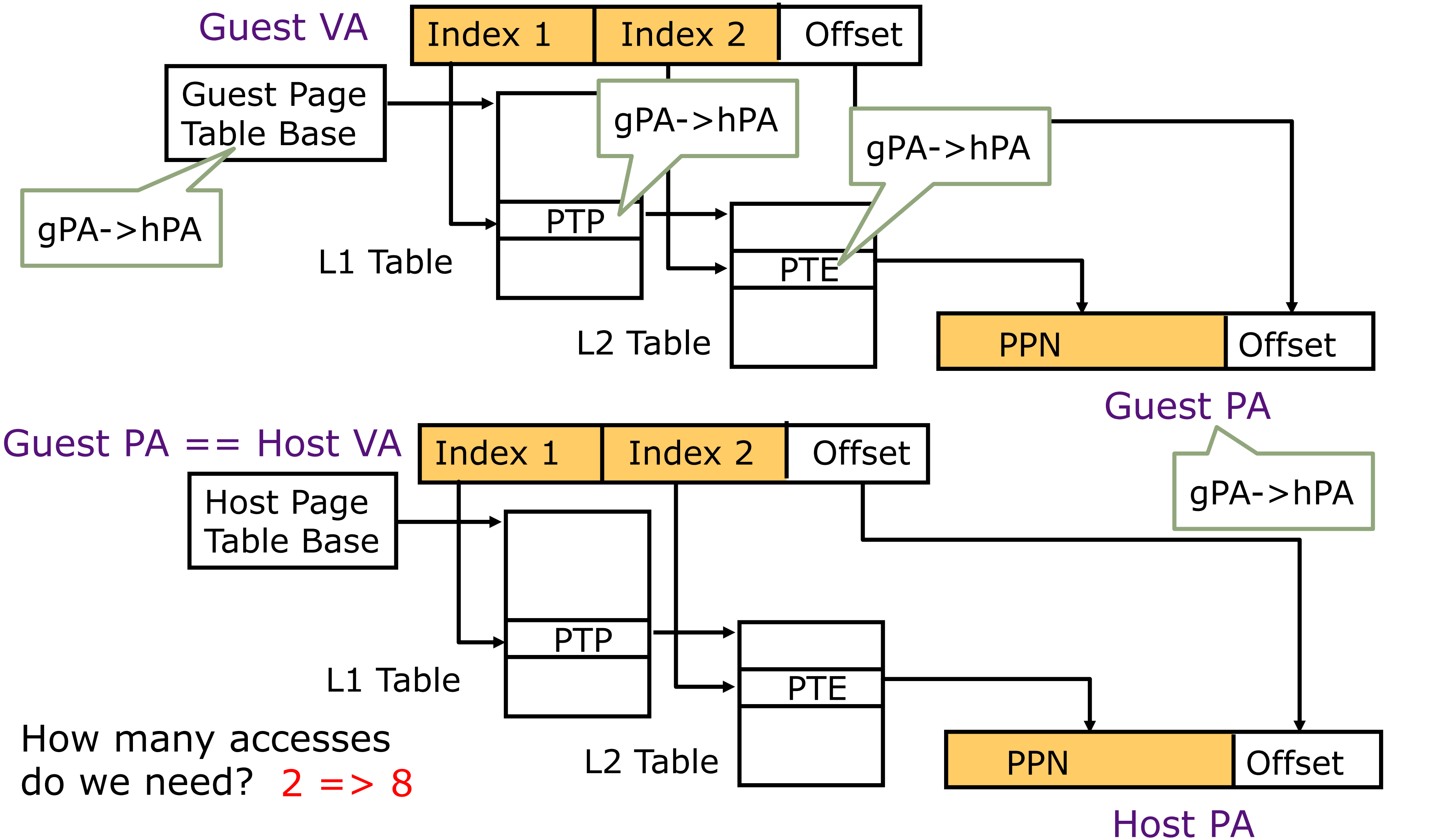
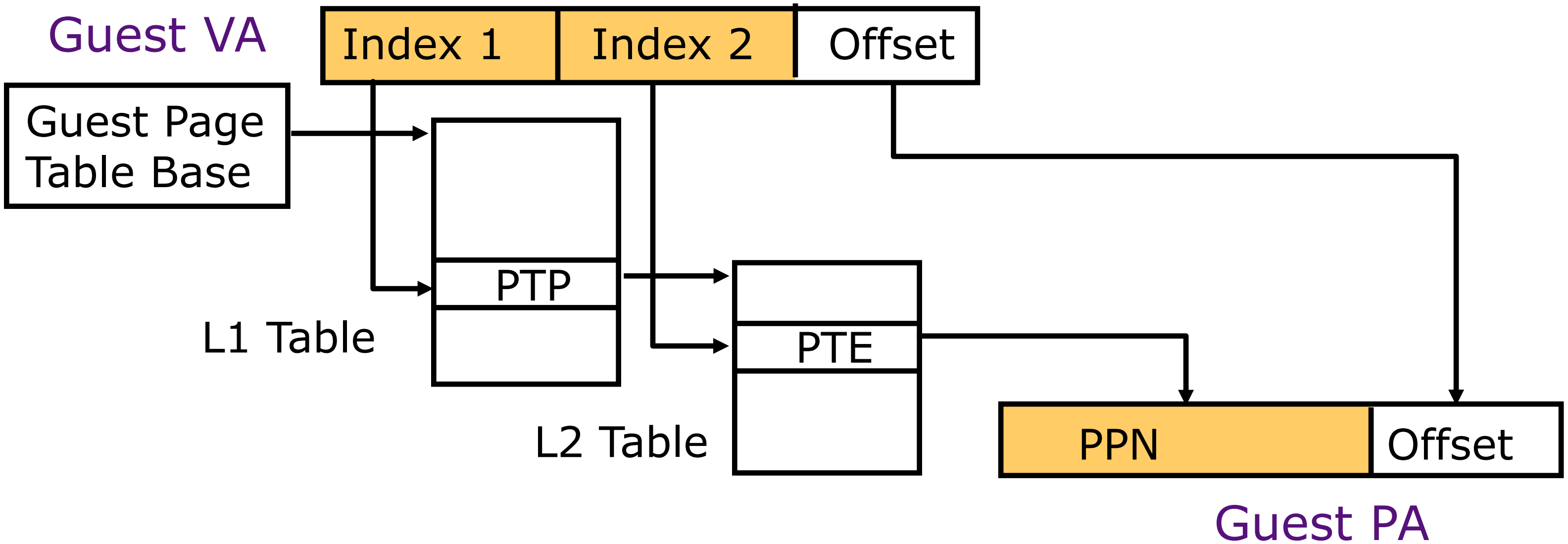


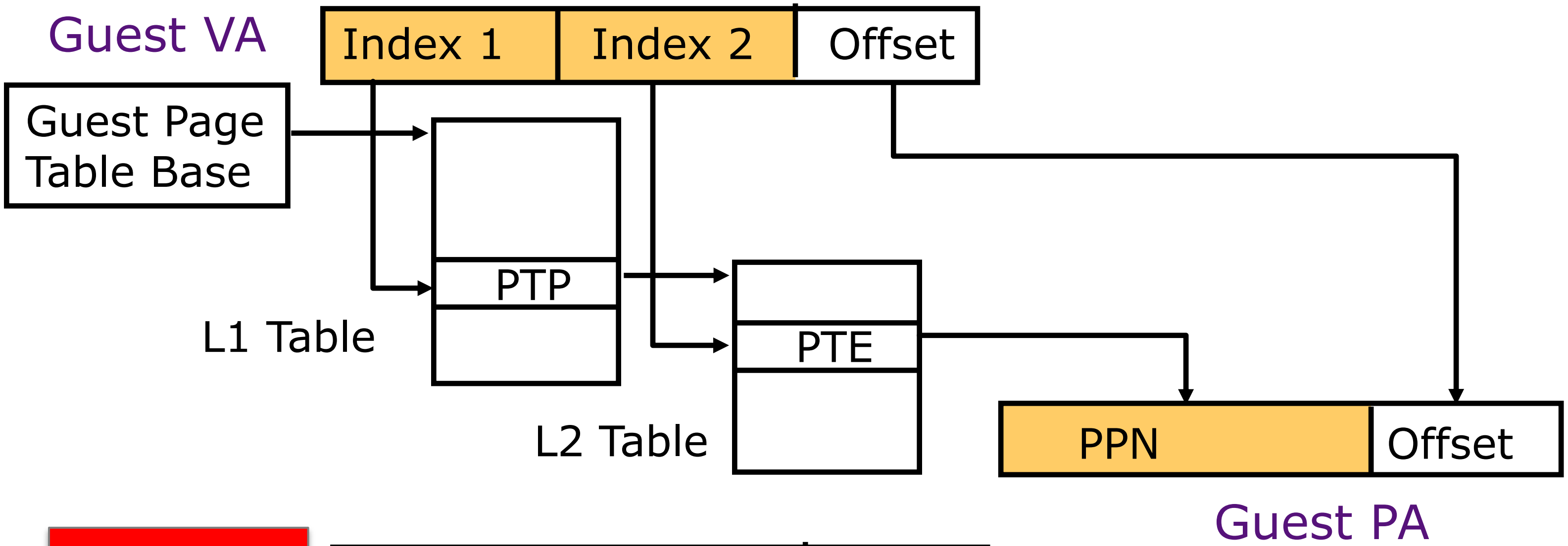
How many accesses do we need? 2 => 8

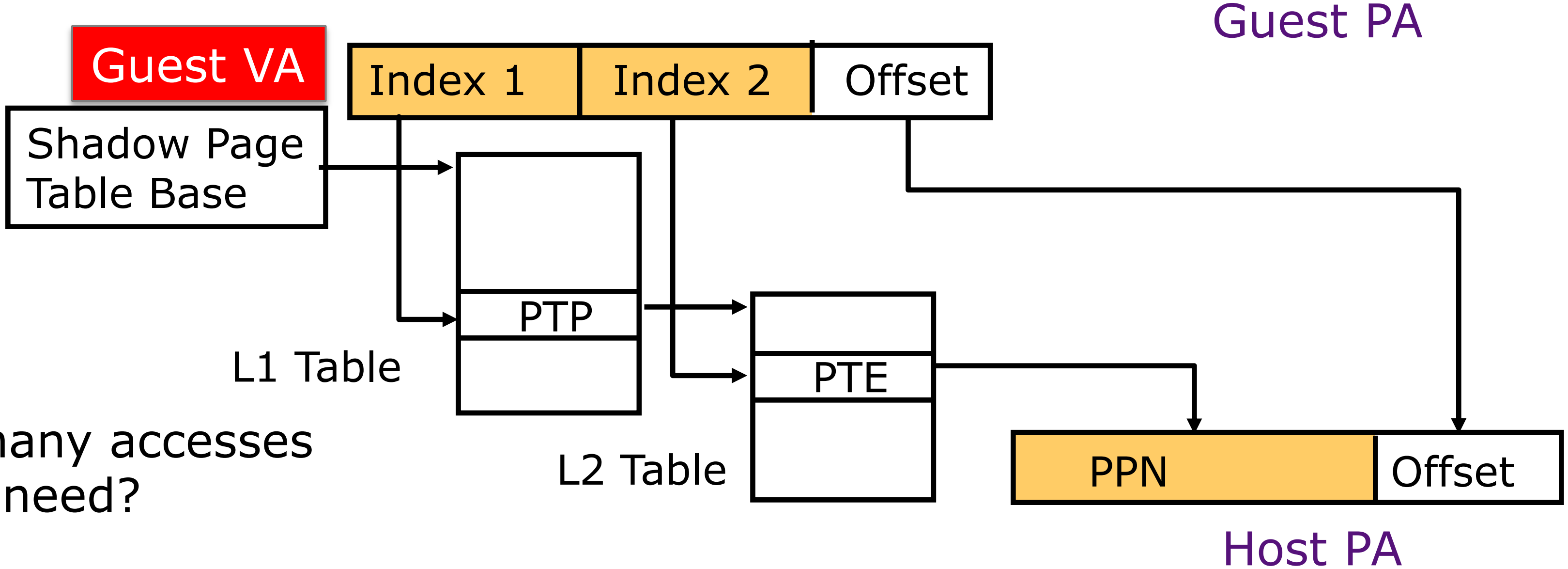
Shadow Page Tables



How many accesses
do we need?

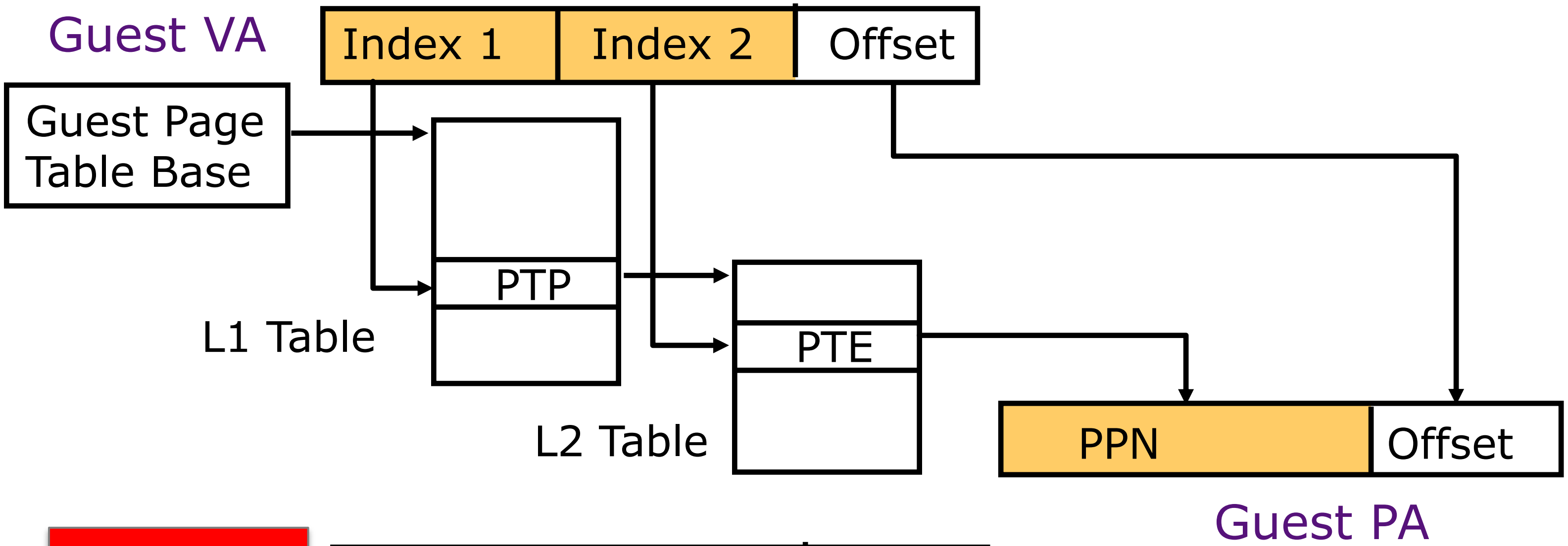
Shadow Page Tables

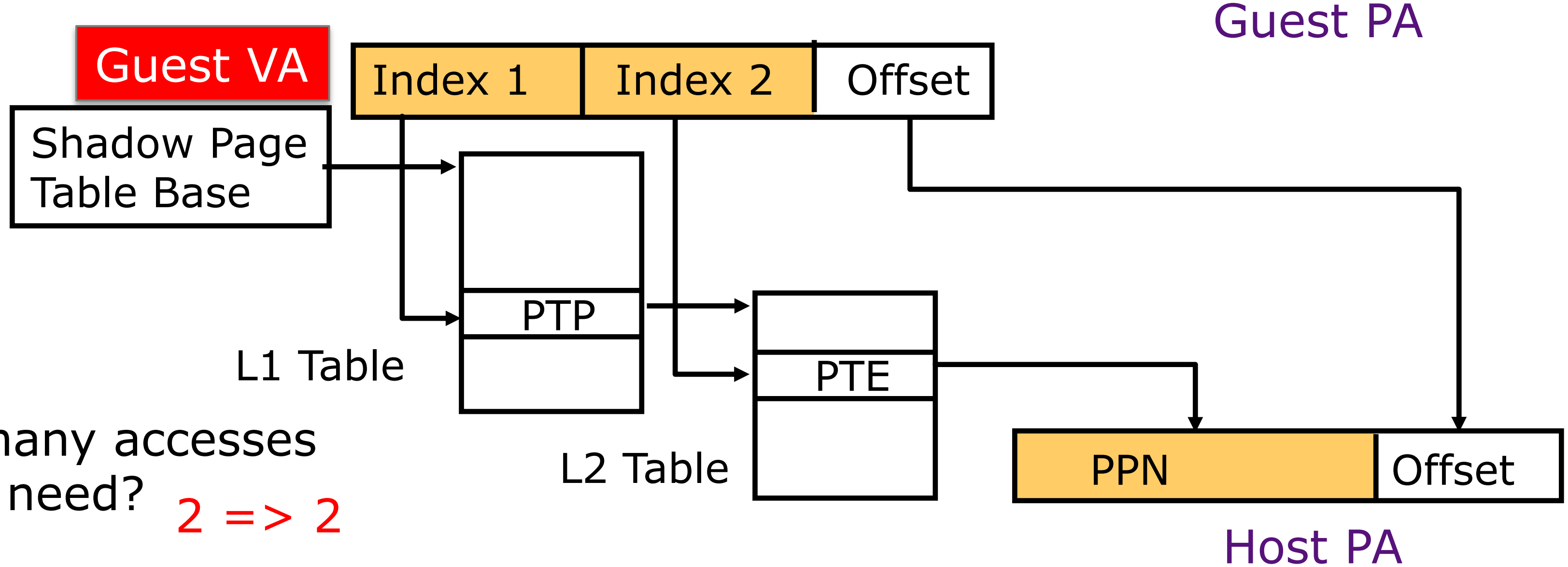




How many accesses do we need?

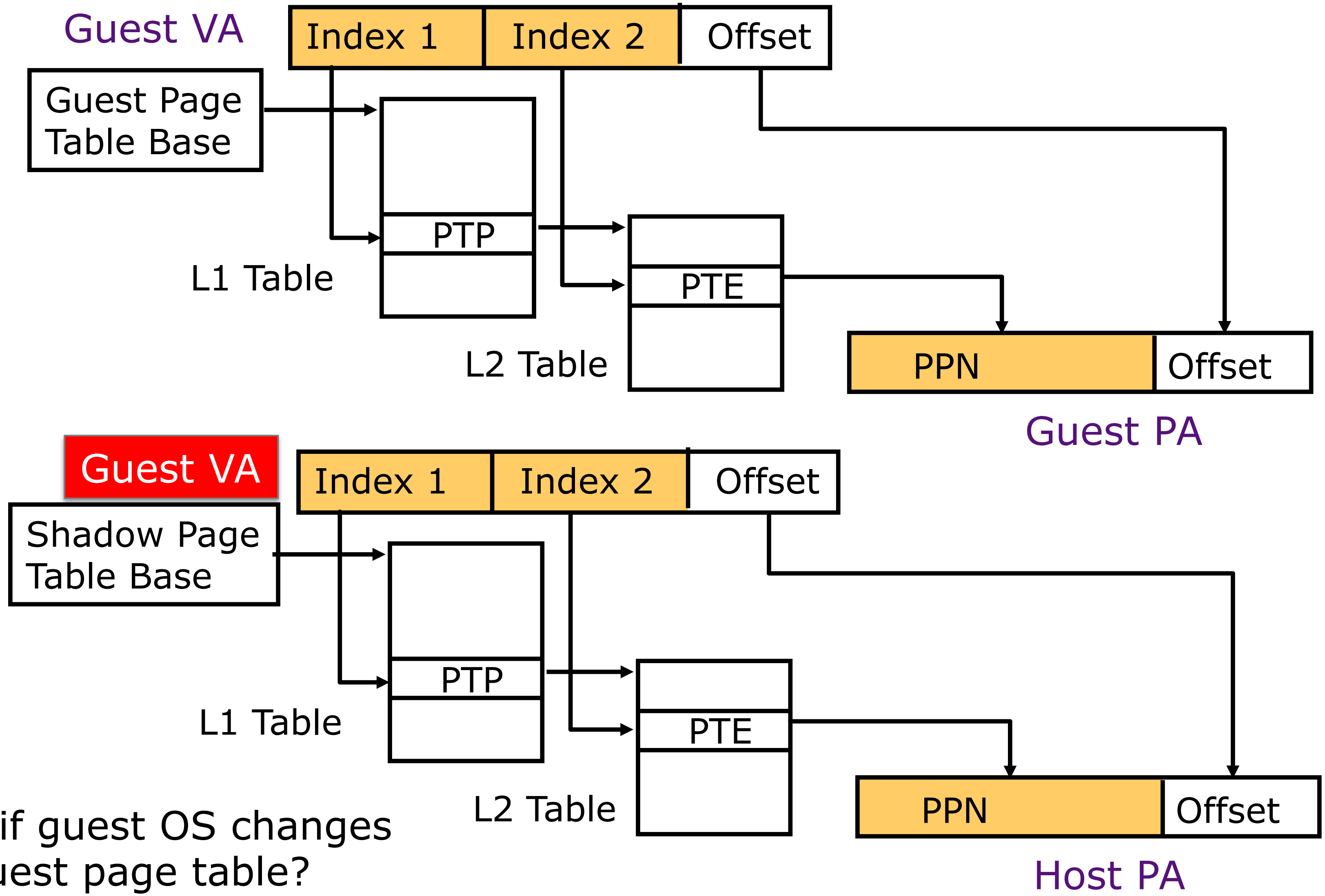
Shadow Page Tables





How many accesses do we need? 2 => 2

Shadow Page Tables



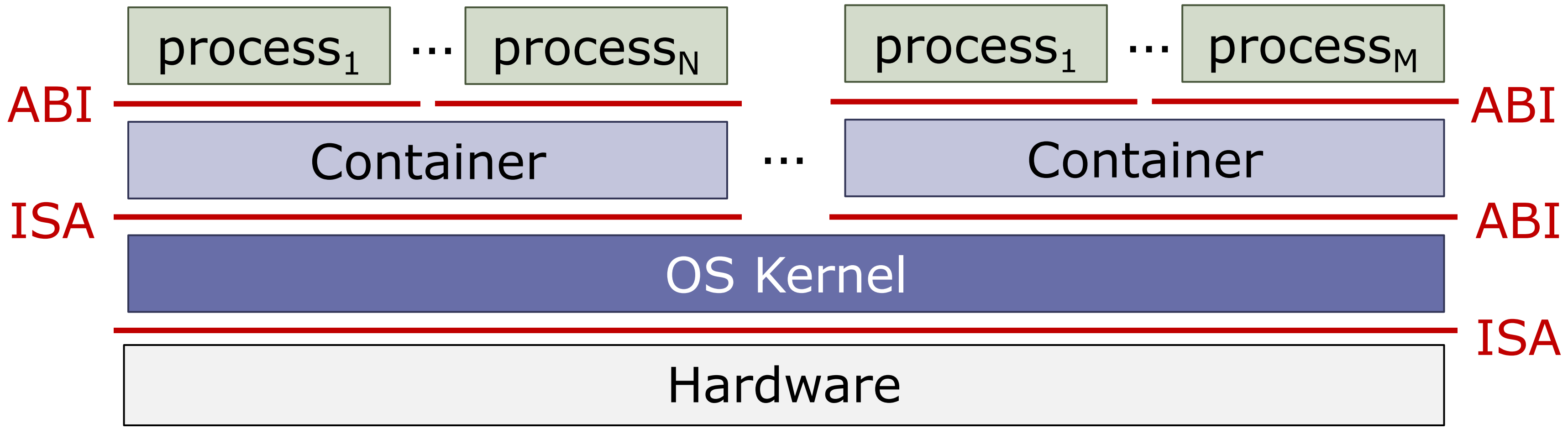
What if guest OS changes the guest page table?

Nested vs Shadow Paging

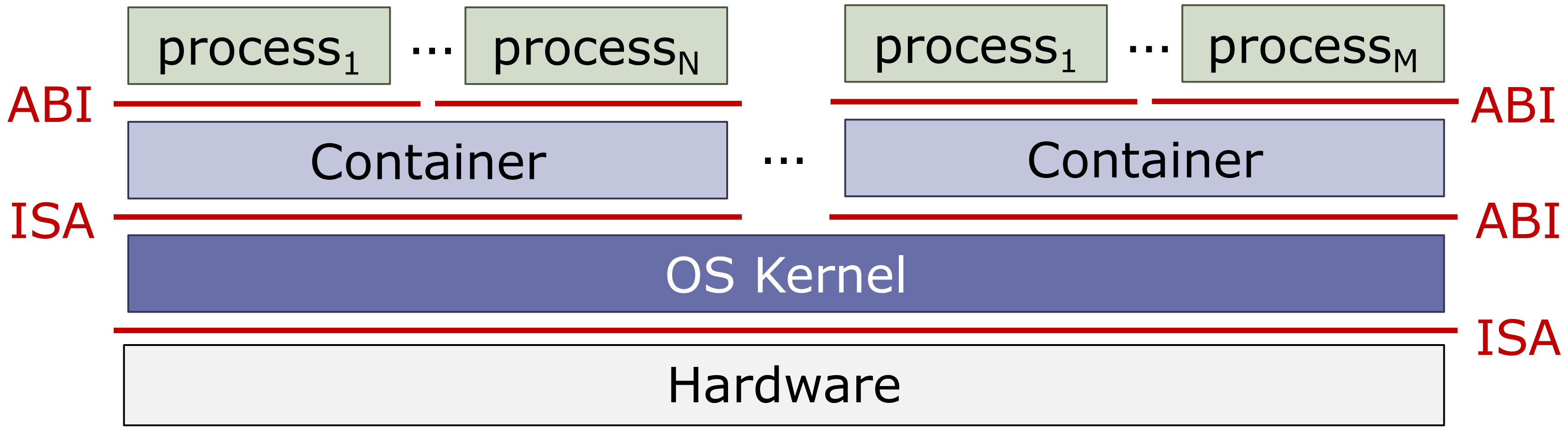
	Native	Nested Paging	Shadow Paging
TLB Hit	VA->PA	gVA->hPA	gVA->hPA
TLB Miss (max)	4	24	4
PTE Updates	Fast	Fast	Uses VMM

On x86-64

Supporting Multiple Process Groups

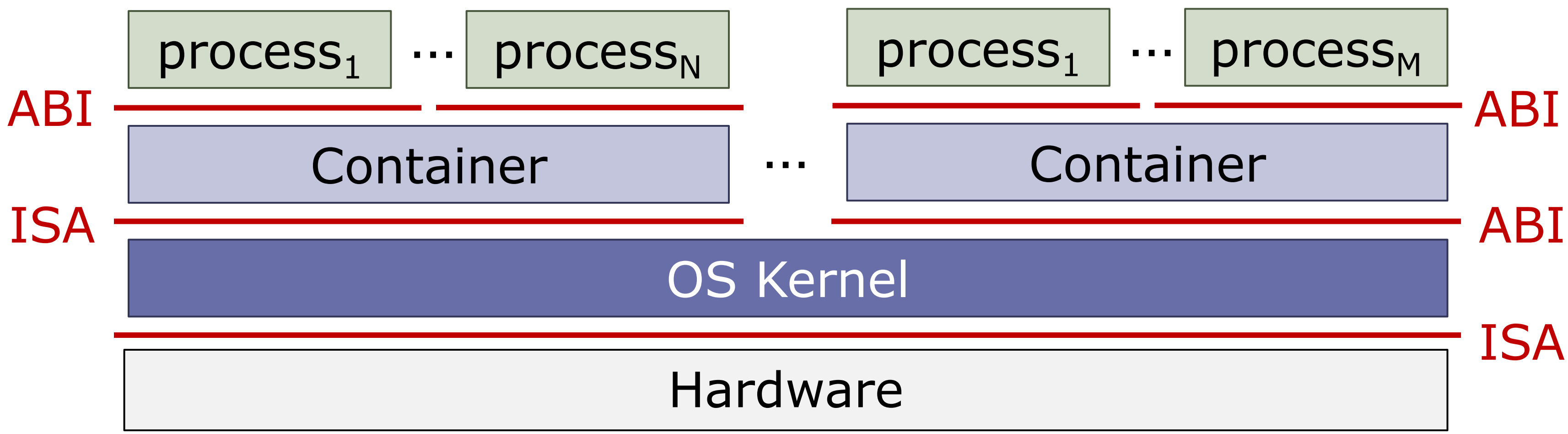


Supporting Multiple Process Groups



- A "container" provides a process group virtual machine to each set of processes

Supporting Multiple Process Groups



- A "container" provides a process group virtual machine to each set of processes
- Container can run directly on OS, which provides a specific OS ABI to the processes in container

Container Semantics

- Isolation between containers is maintained by the OS, which supports a virtualized set of kernel calls.
  - Therefore, processes in all containers must target the same OS*

- Per Container Resources
  - Set of processes (each with a virtual memory space)
  - Set of filesystems
  - Set of network interfaces and ports
  - Selected devices

*Or closely related variants

Coming Spring 2023 …

- 6.S984: Datacenter Computing
- Instructor: Christina Delimitrou
- Short description:
  - Datacenter Computing explores the end-to-end stack of modern datacenters, from hardware and OS all the way to resource managers and programming frameworks.
  - The class will also explore cross-cutting issues, such as ML for systems, energy efficiency, availability, security, and reliability.
  - The main deliverable for the course is a semester-long research project on cloud computing, done in groups of 2-3 students. We will provide a list of suggested projects, but students are also encouraged to suggest their own.
- Lecture time: two 1.5-hour meetings per week

Thank you!