Virtualization

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M.I.T.

Abstractions

Devices
Materials
Atoms

Abstractions

Digital design

Combinational and sequential circuits

Devices

Materials

Atoms

Abstractions

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

Computer architecture

Processors, caches, pipelining

Digital circuits

Digital design

Combinational and sequential circuits

Bits, Logic gates

Devices

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Atoms

Evolution in Number of Users

IBM 1620
1959

Single User

Runtime loaded with program

Evolution in Number of Users

IBM 1620 1959	IBM 360 1960s
	
<u>Single User</u>	<u>Multiple Users</u>
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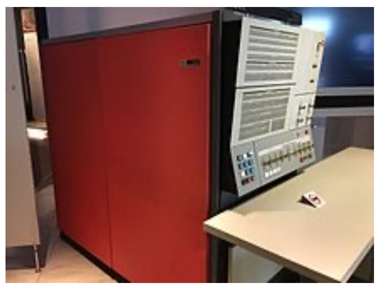
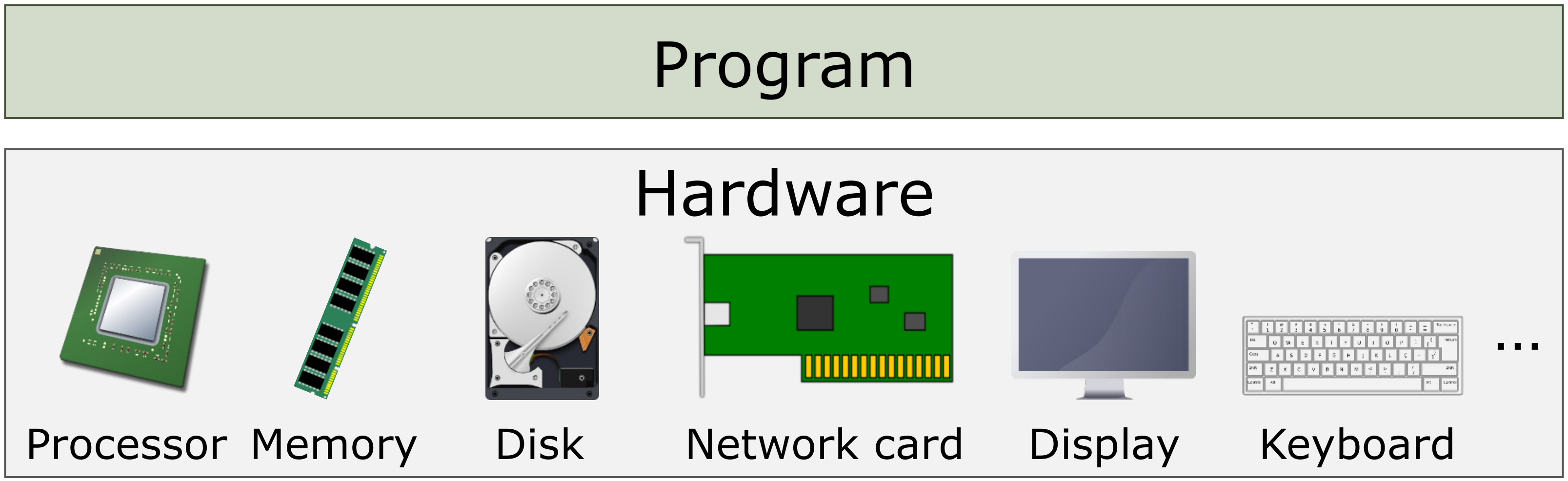
			
<u>Single User</u>	<u>Multiple Users</u>	<u>Single User</u>	<u>Multiple Users</u>
Runtime loaded with program	OS for sharing resources	OS for sharing resources	Multiple OSs

Single-Program Machine



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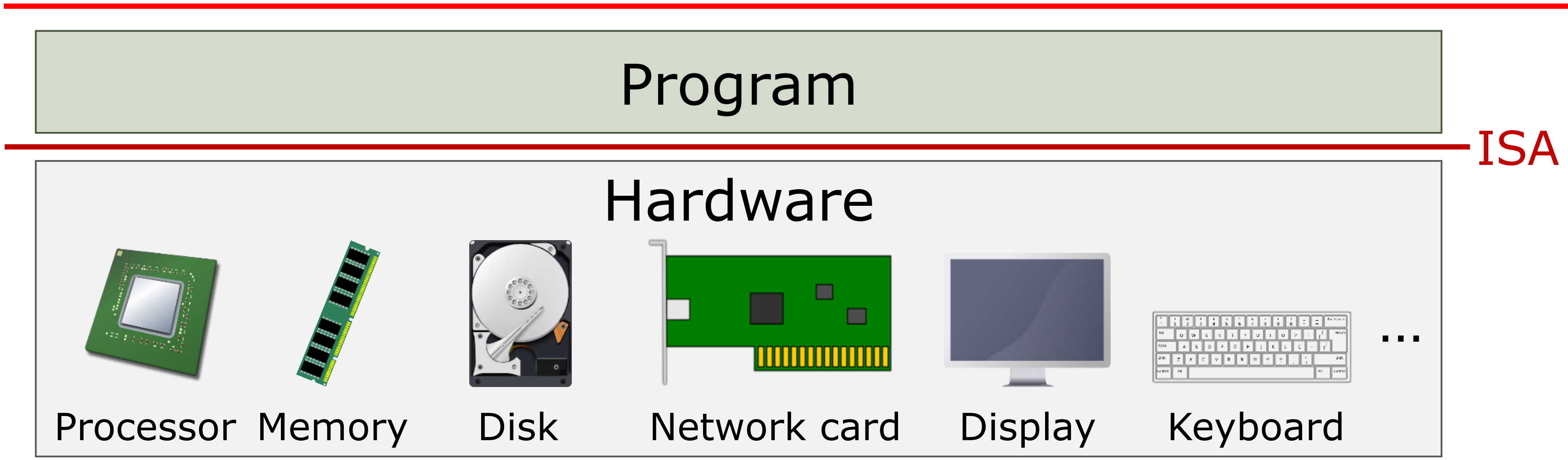
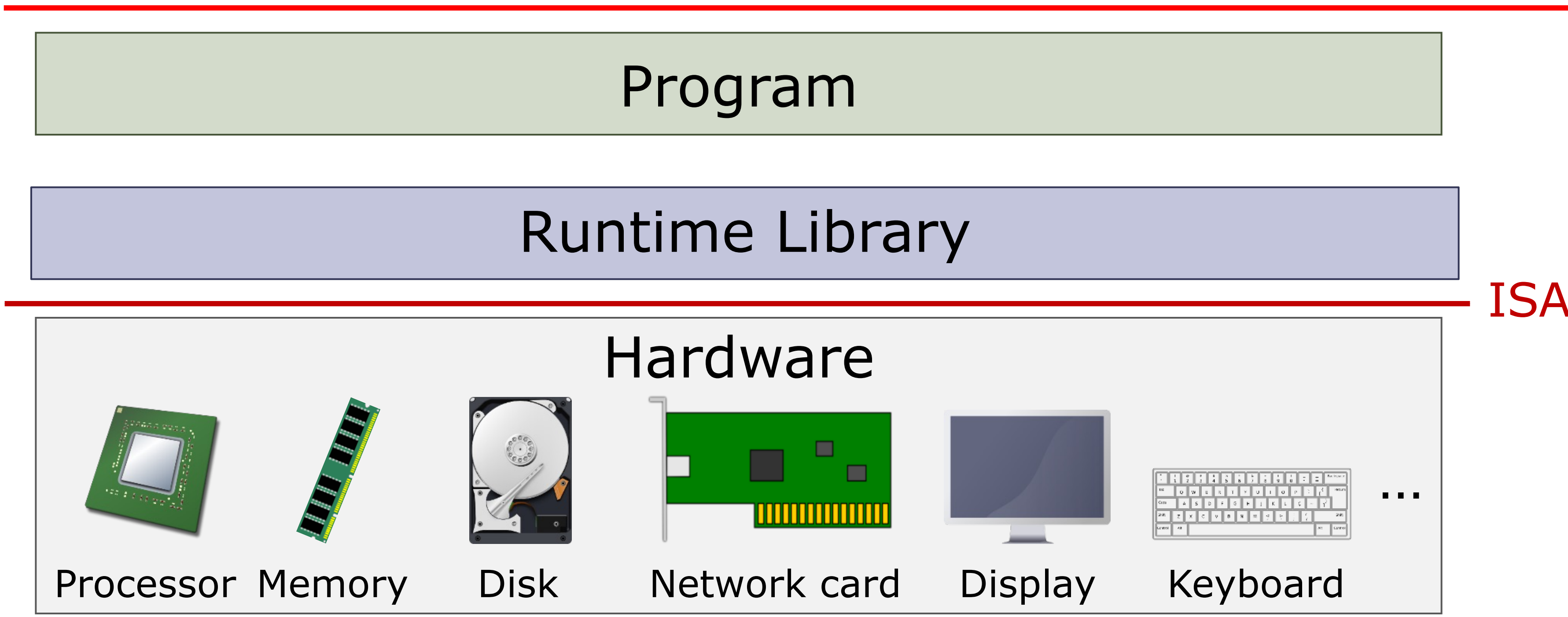


- Hardware executes a single program and has direct and complete access to all hardware resources
- The ISA is the interface between software and hardware:
  - Program counter
  - General purpose registers
  - Memory

Single-Program Machine (with RTL)



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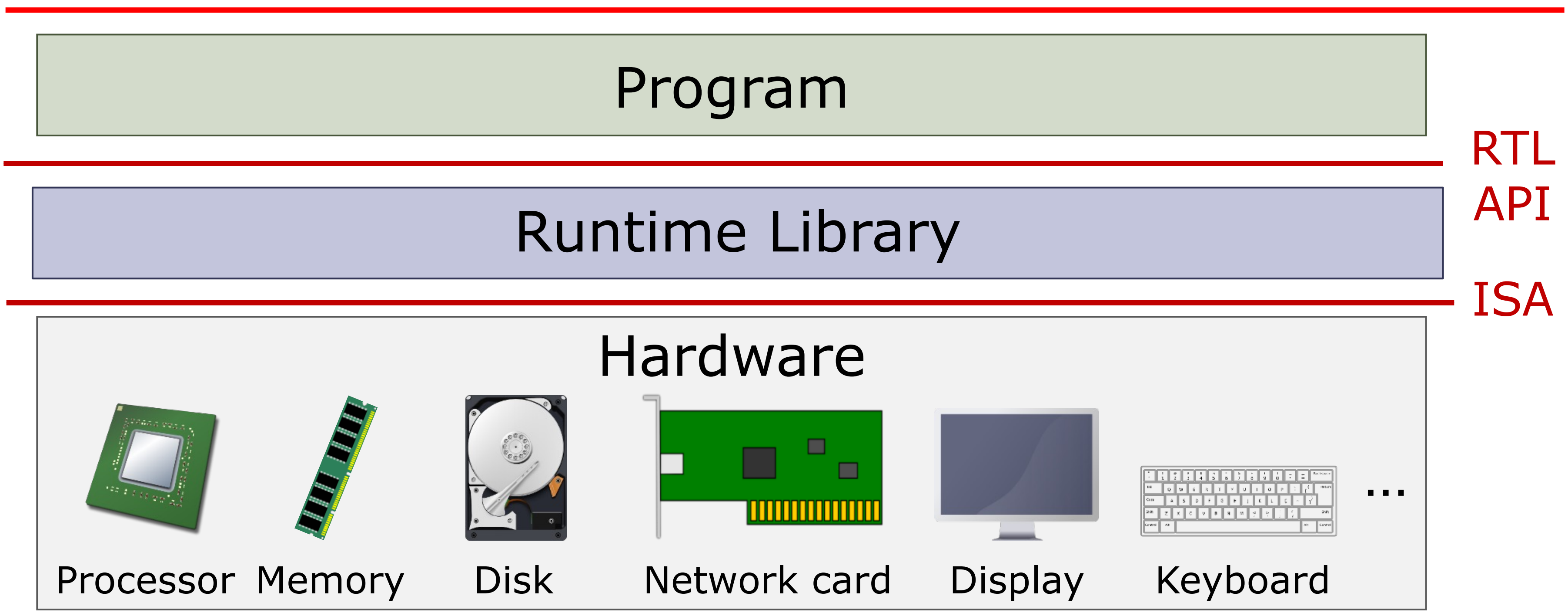

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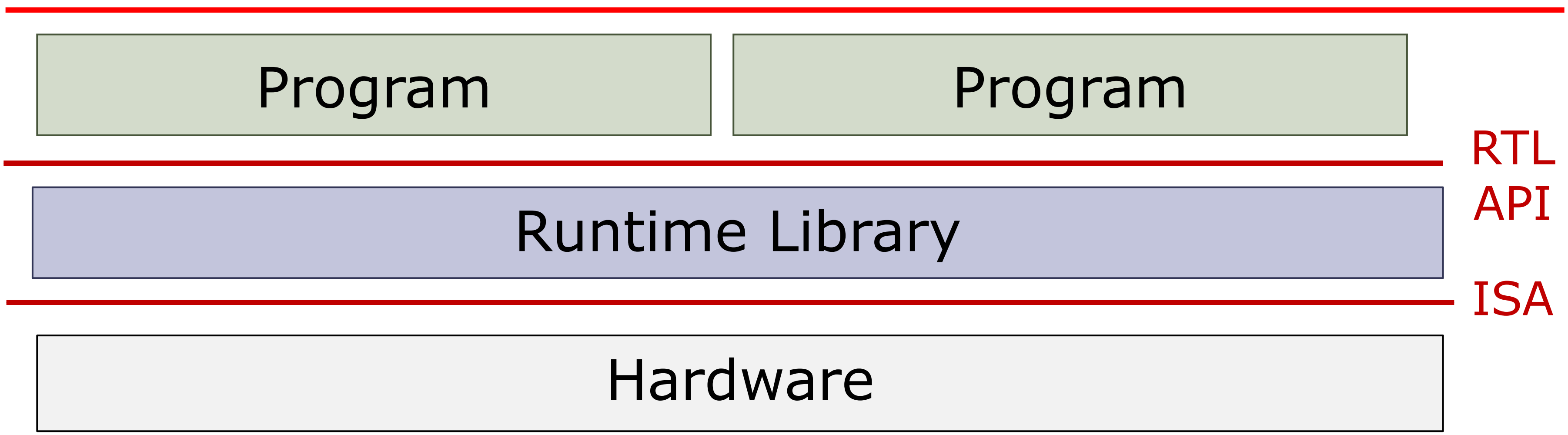

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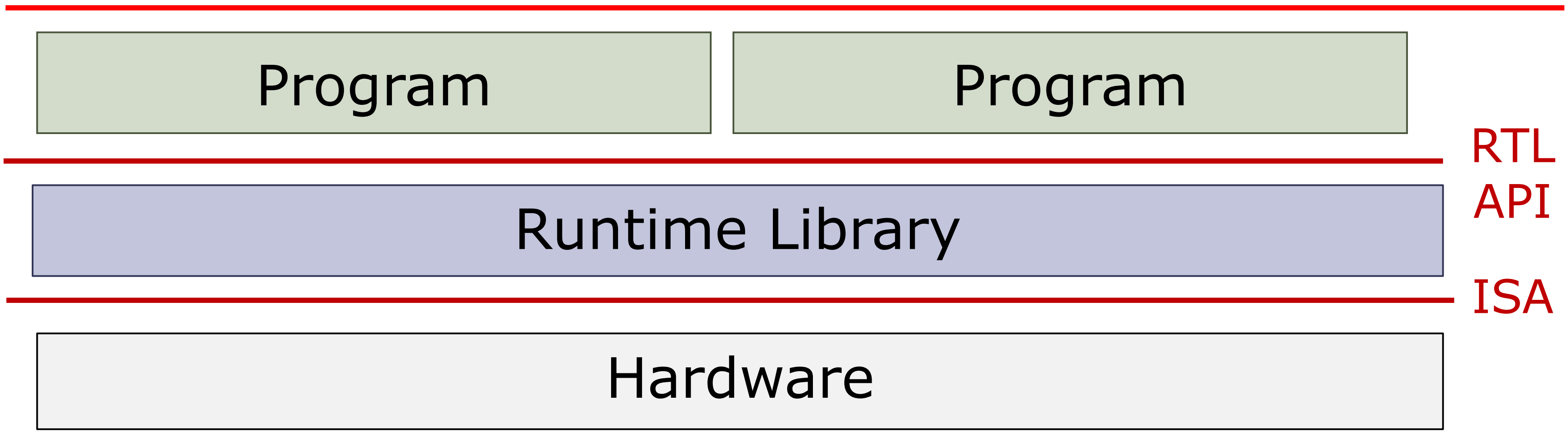

Any problems?

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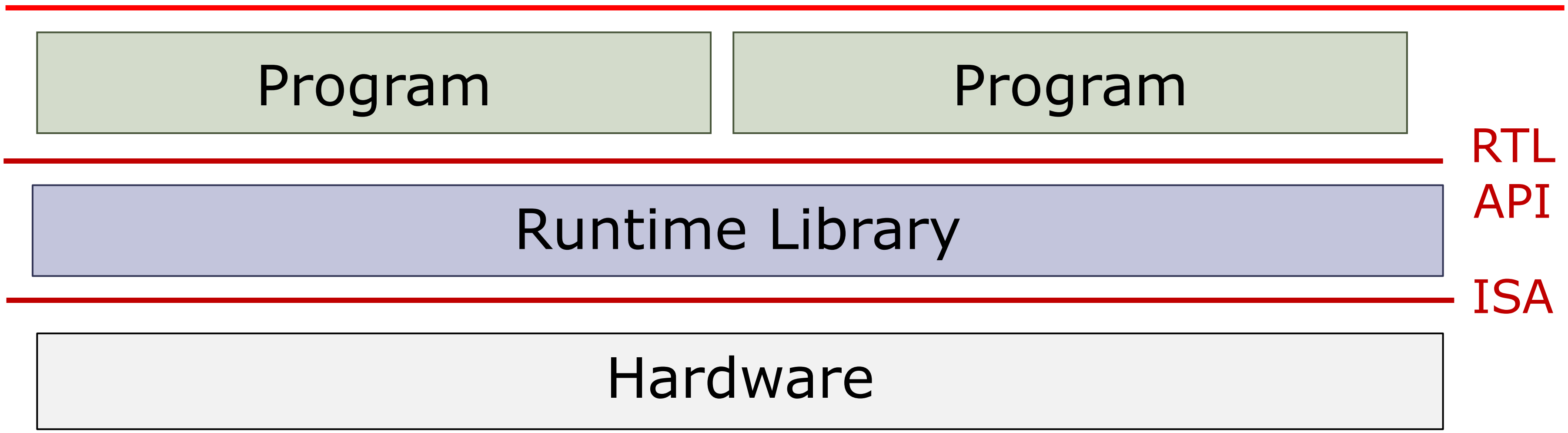
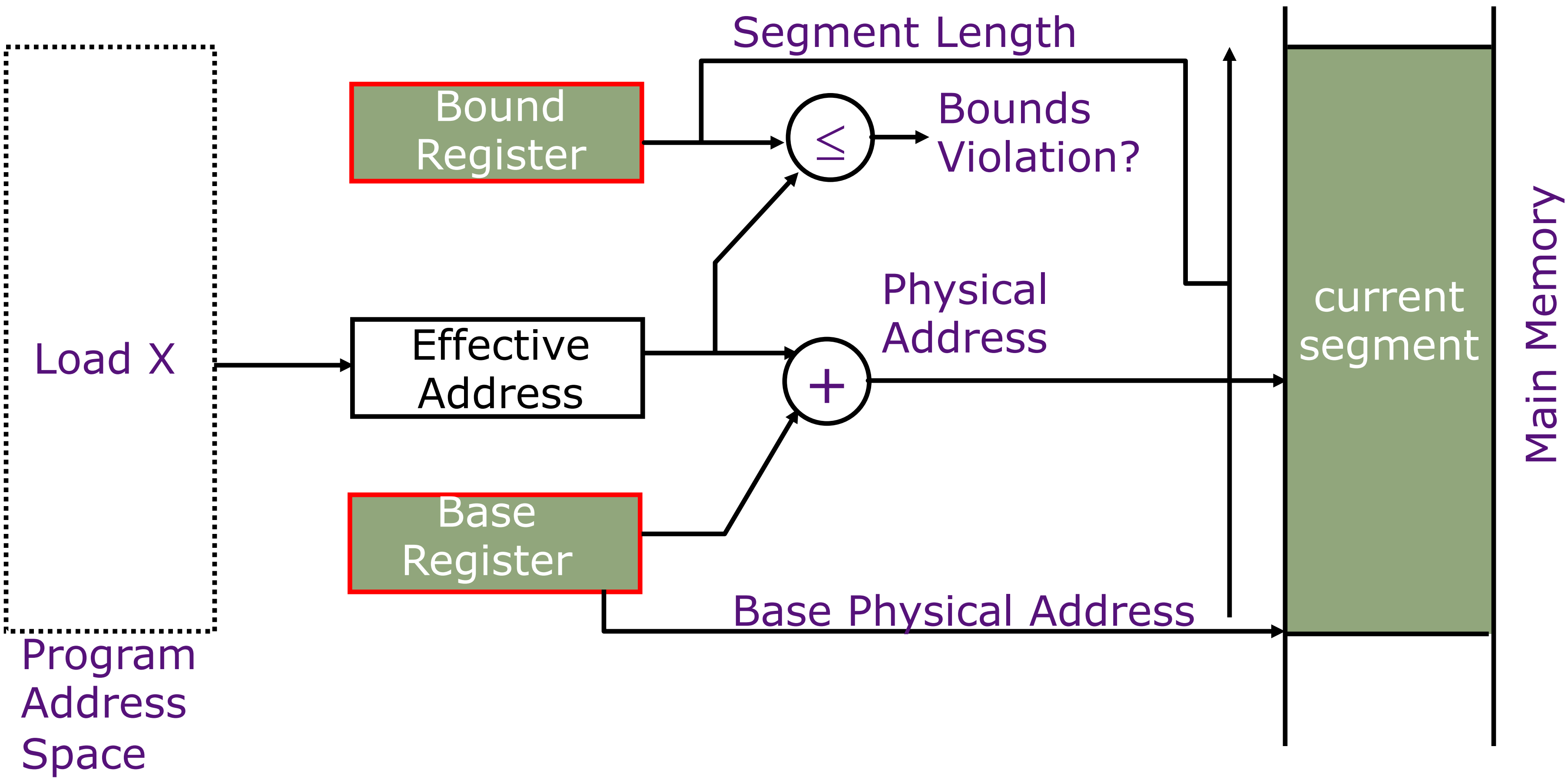


Any problems? security

Simple Base and Bound Translation



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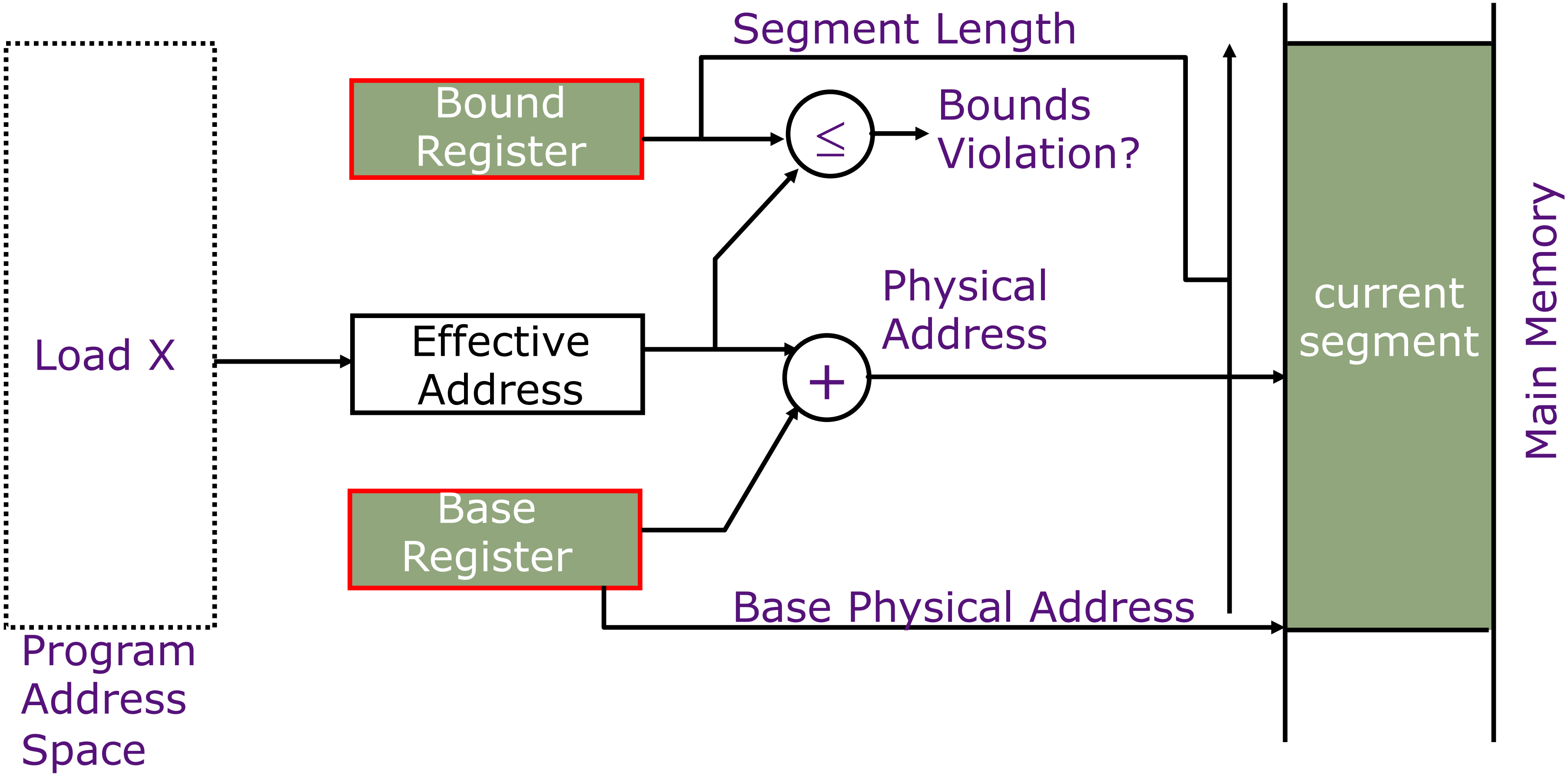

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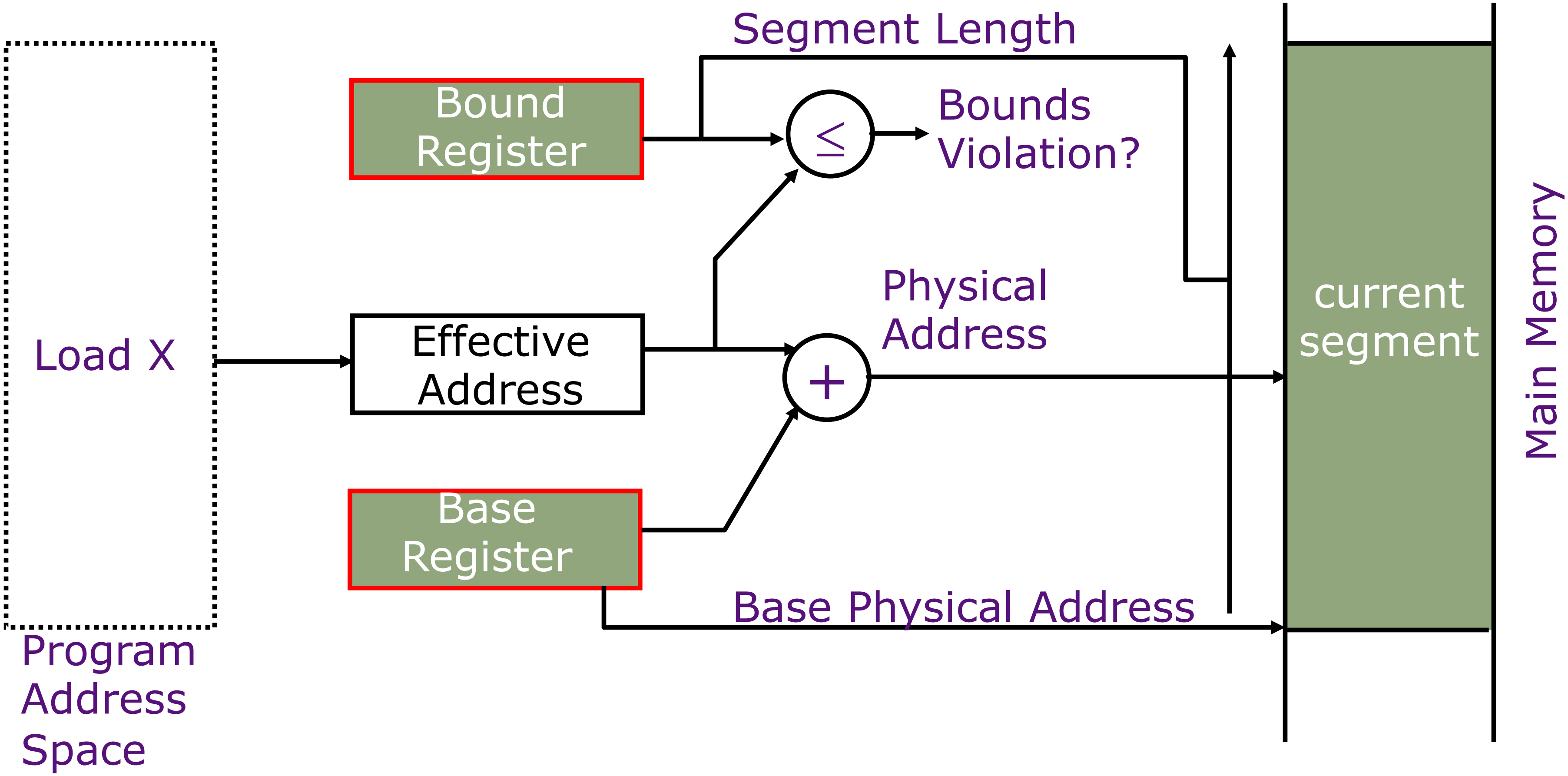


Introduce a new privileged mode in which the base and bounds registers are visible/accessible.

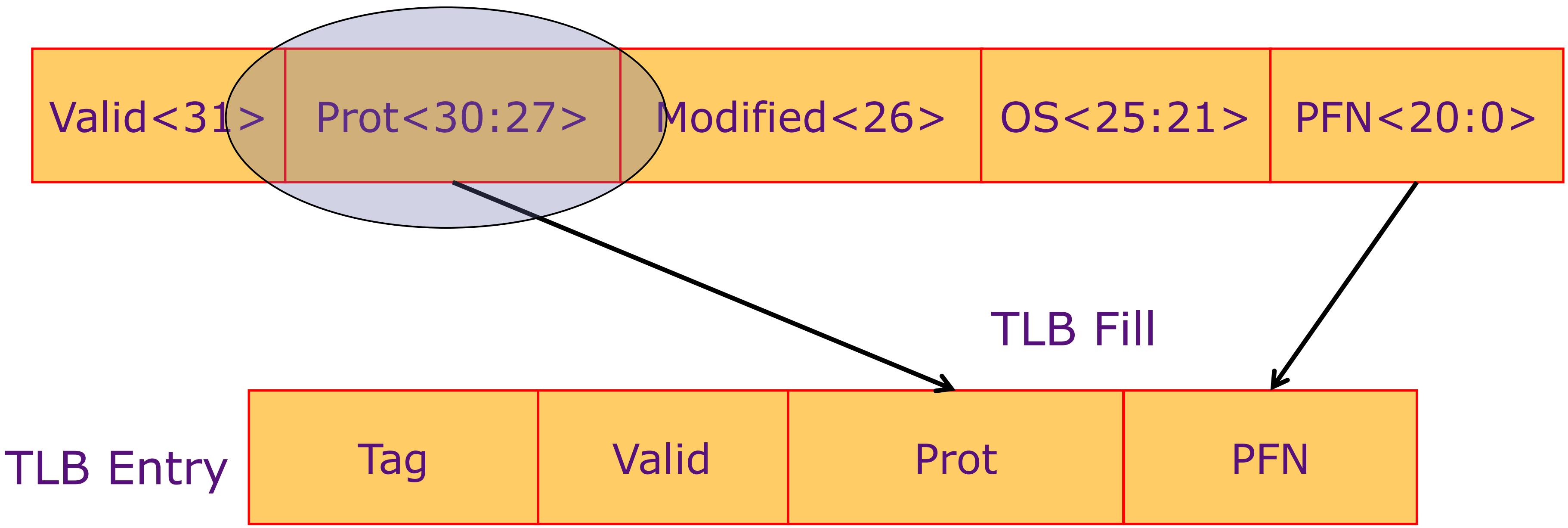
Protecting Memory

Page Table Entry

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

Protecting Memory

Page Table Entry



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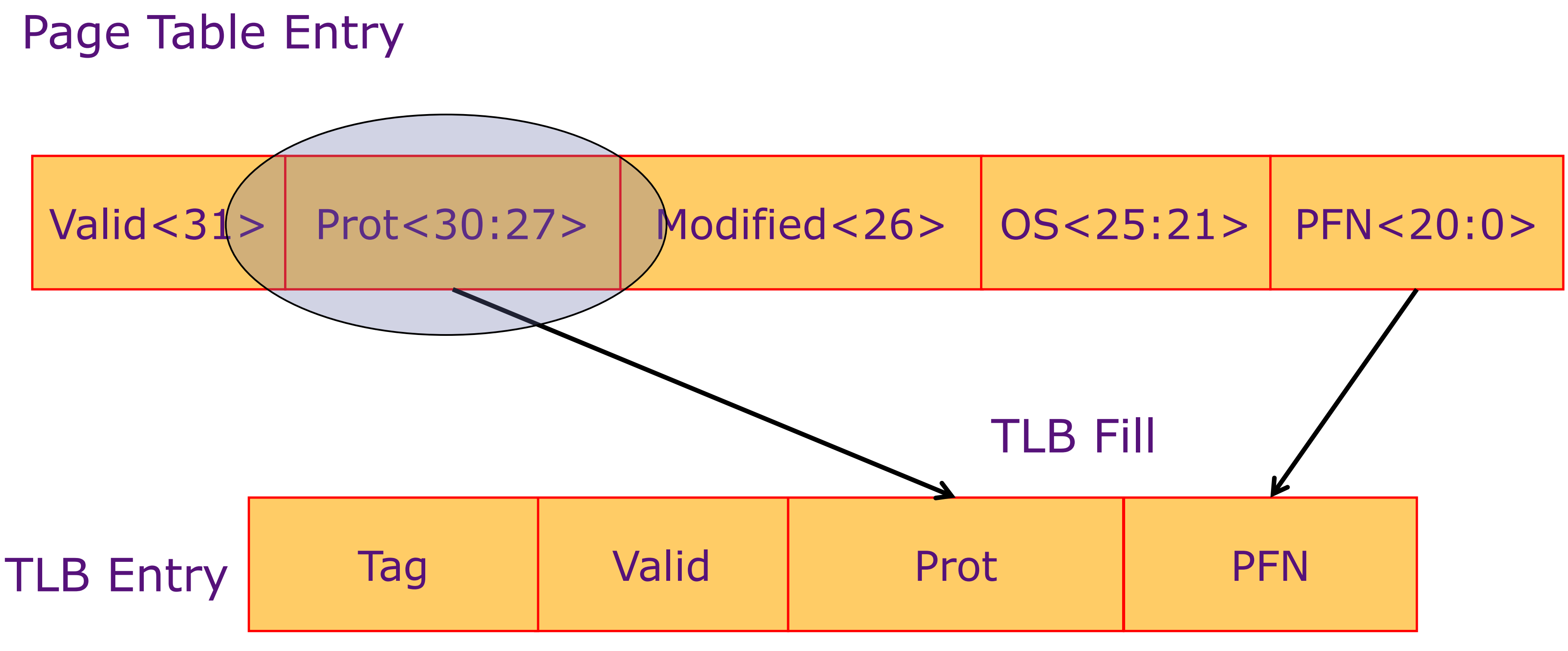
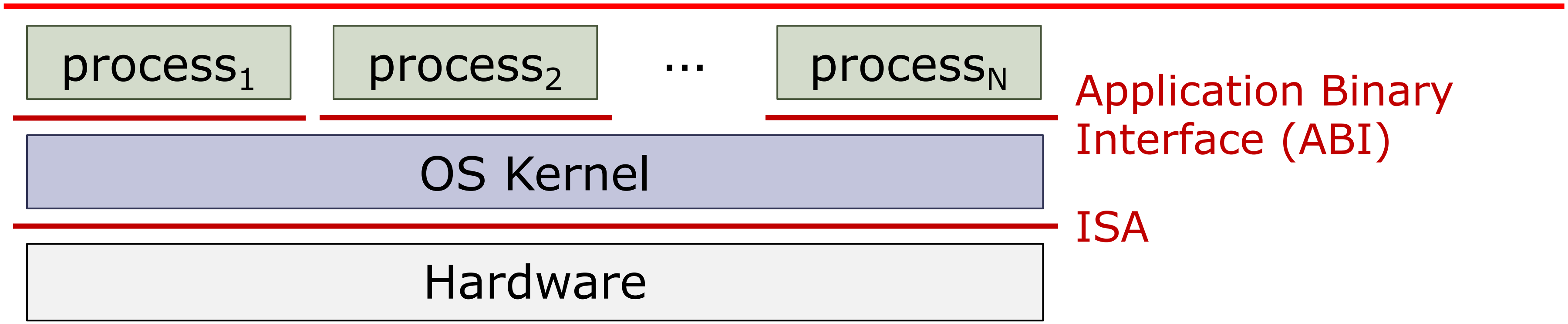


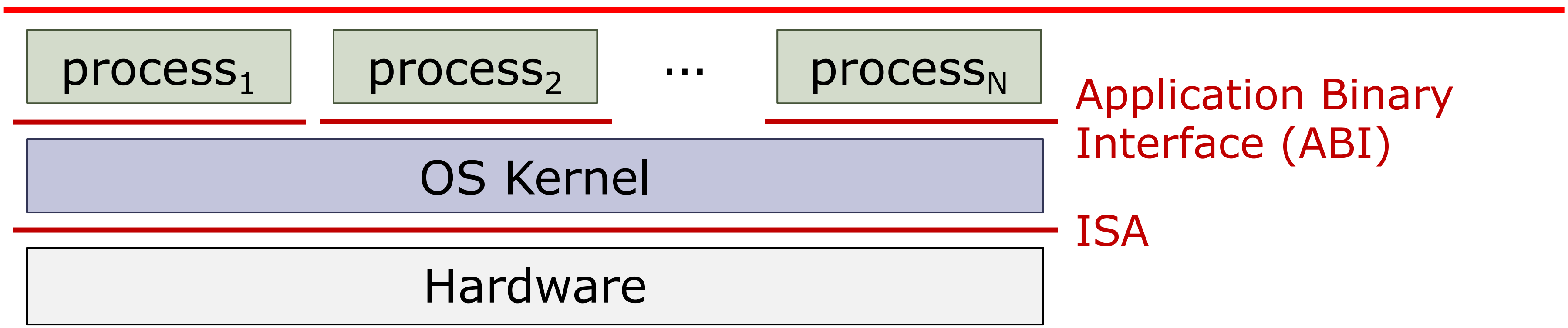
- TLB access checks if protection allows access for current mode
- TLB fills require read/copy page table data -> security sensitive

Operating Systems



- Operating System (OS) goals:

Operating Systems



- Operating System (OS) goals:
  - Abstraction: OS hides details of underlying hardware
    - e.g., a process can open and access files instead of issuing raw commands to the disk
  - Resource management: OS controls how processes share hardware (CPU, memory, disk, etc.)
  - Protection and privacy: Processes cannot access each other's data

Operating System Mechanisms

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

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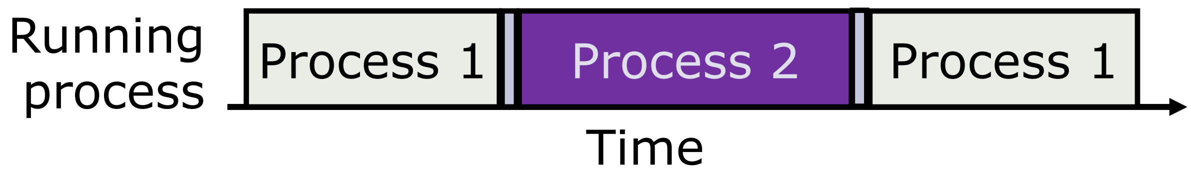

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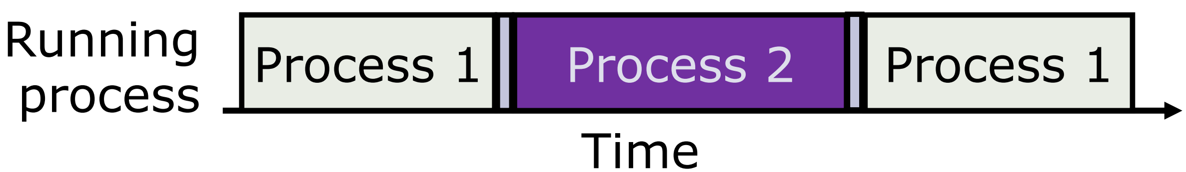
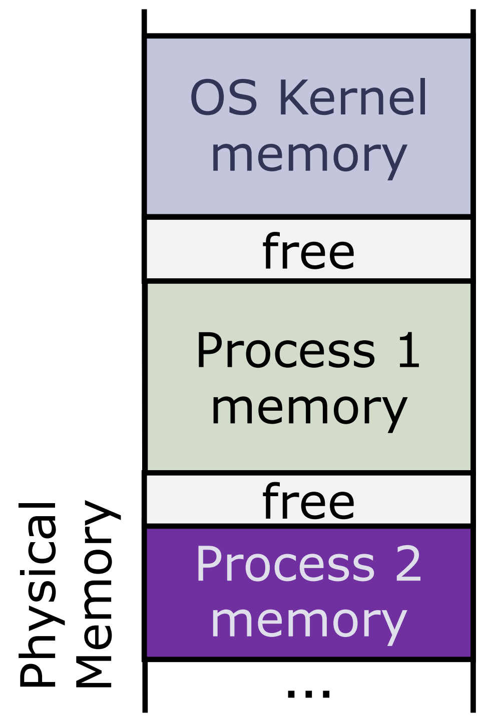


- The OS kernel provides a private address space to each process
  - Each process is allocated space in physical memory by the OS
  - A process is not allowed to access the memory of other processes



ISA Extensions to Support OS

- Two modes of execution: user and supervisor
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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

user mode

kernel mode

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Pass arguments;
Save app state;
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Why?

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Kernel routine

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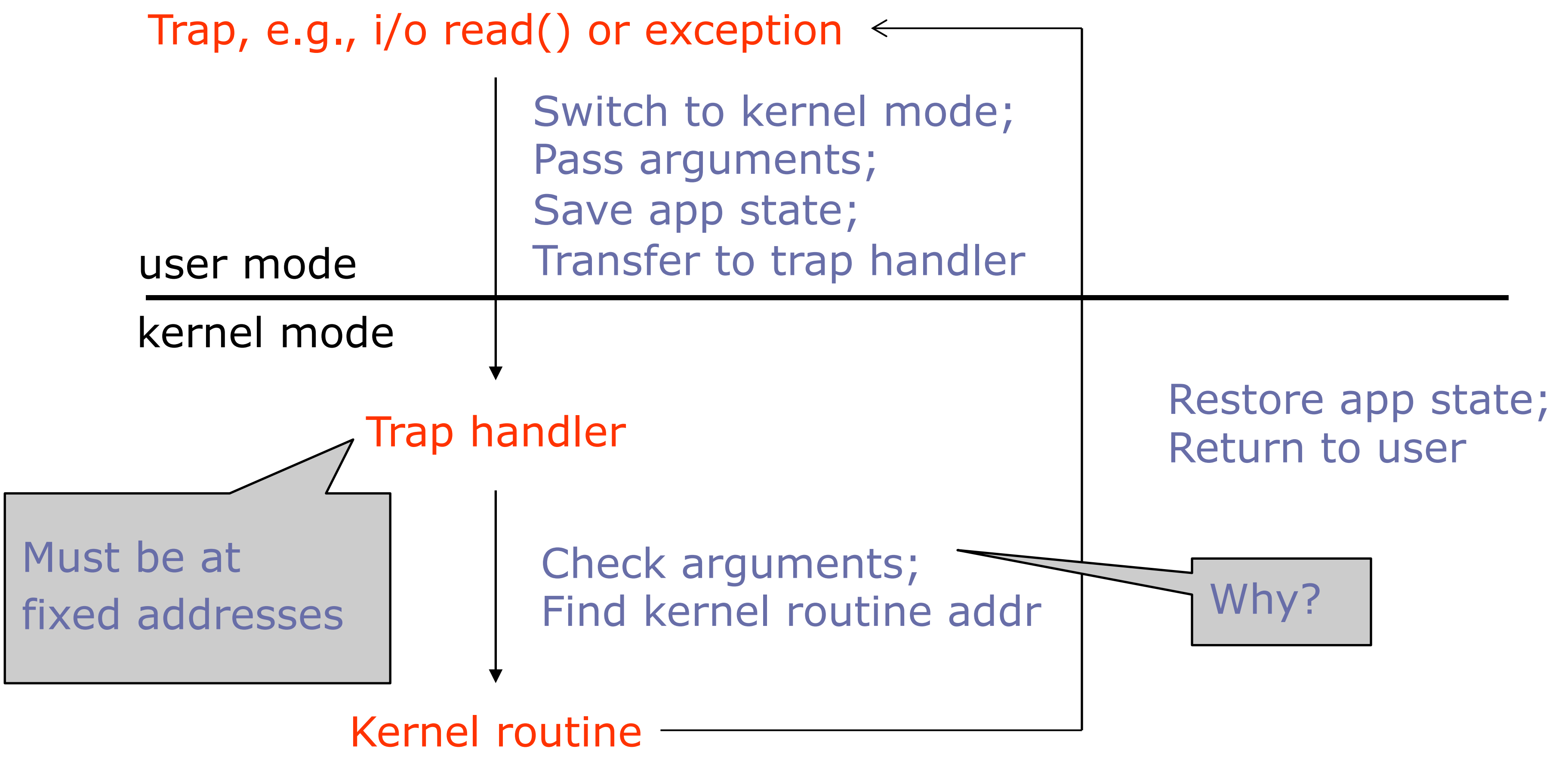
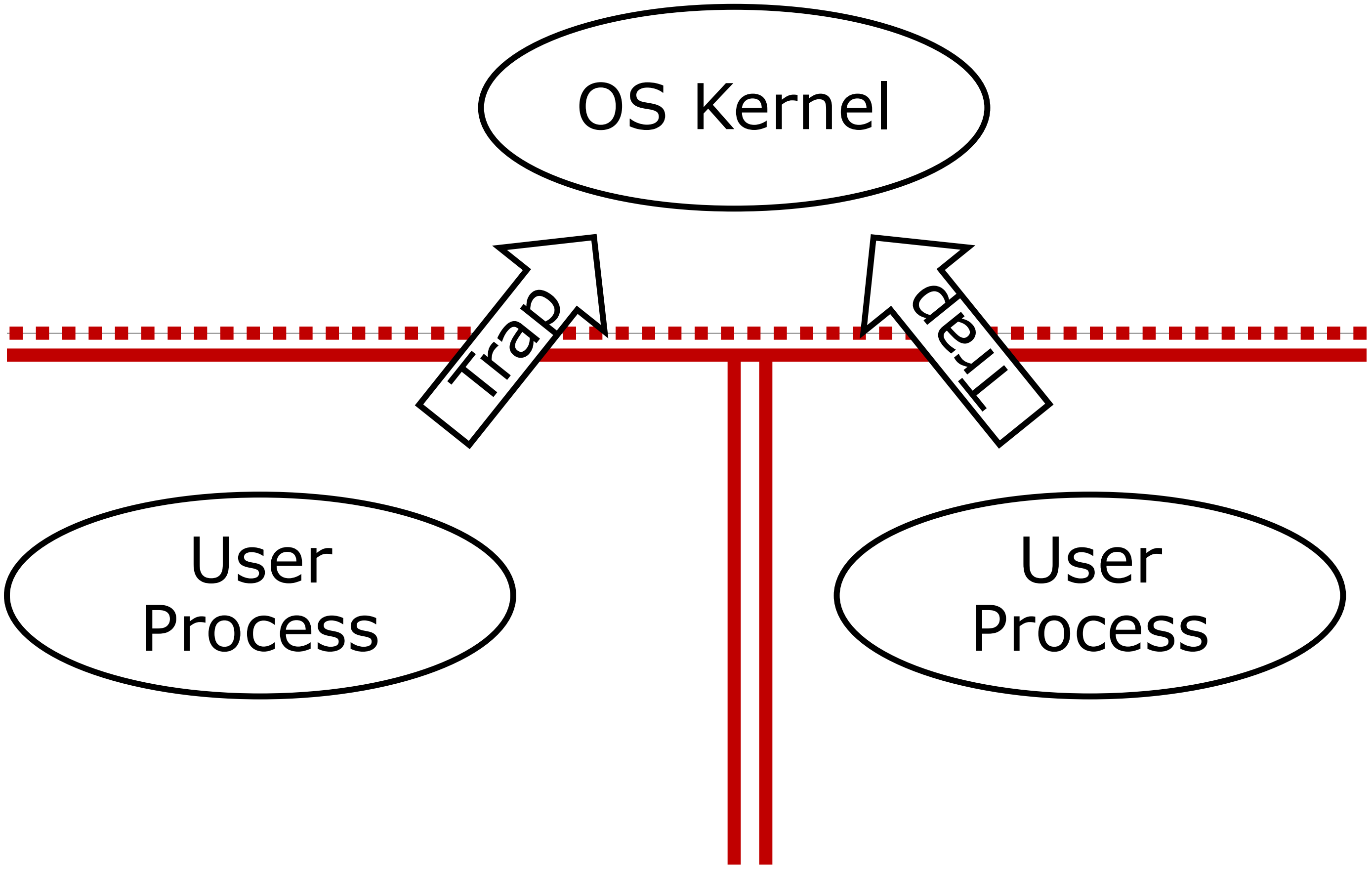


Protection – Single OS



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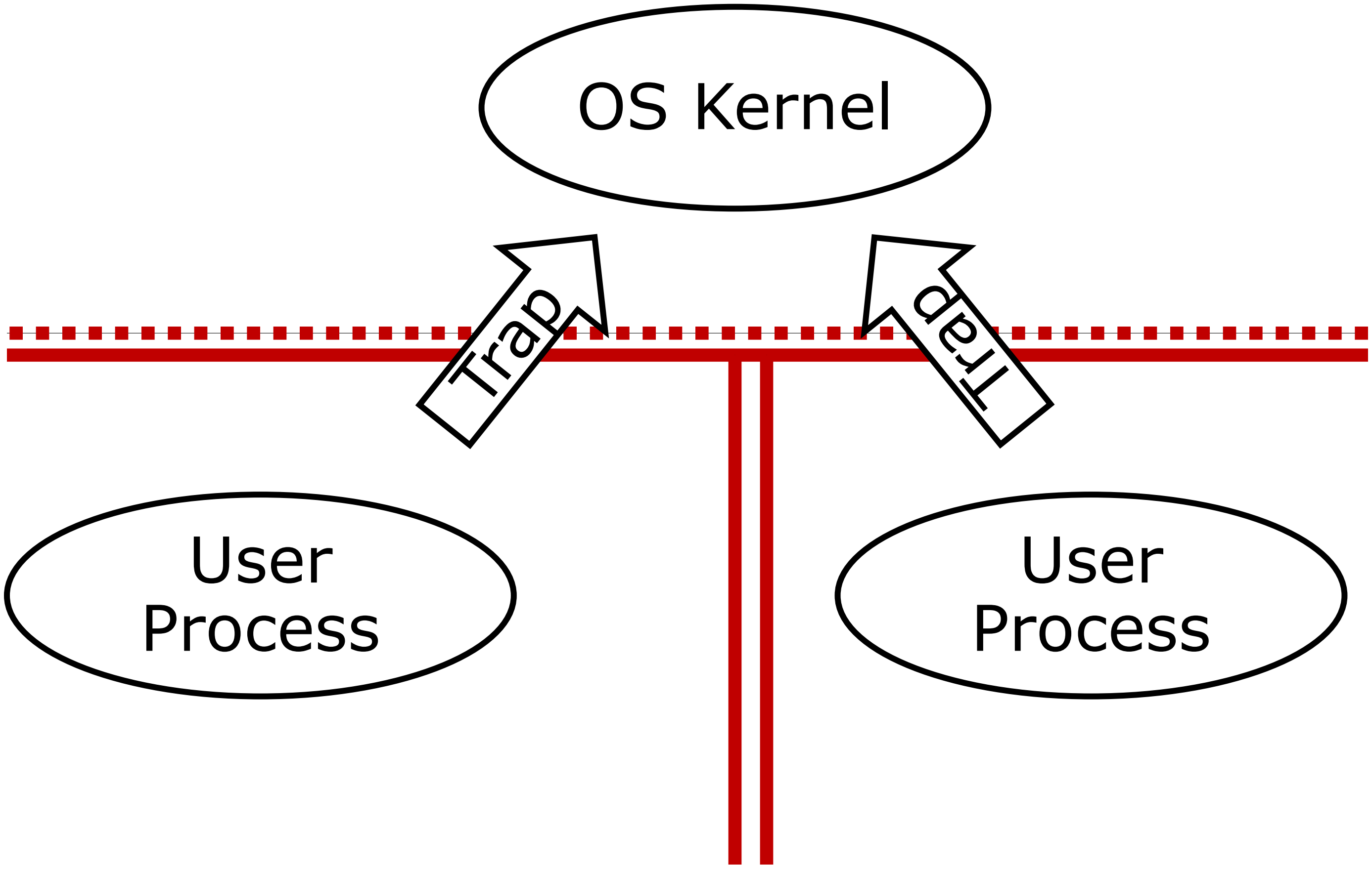

Key idea: Provides a strong abstraction that cannot be escaped

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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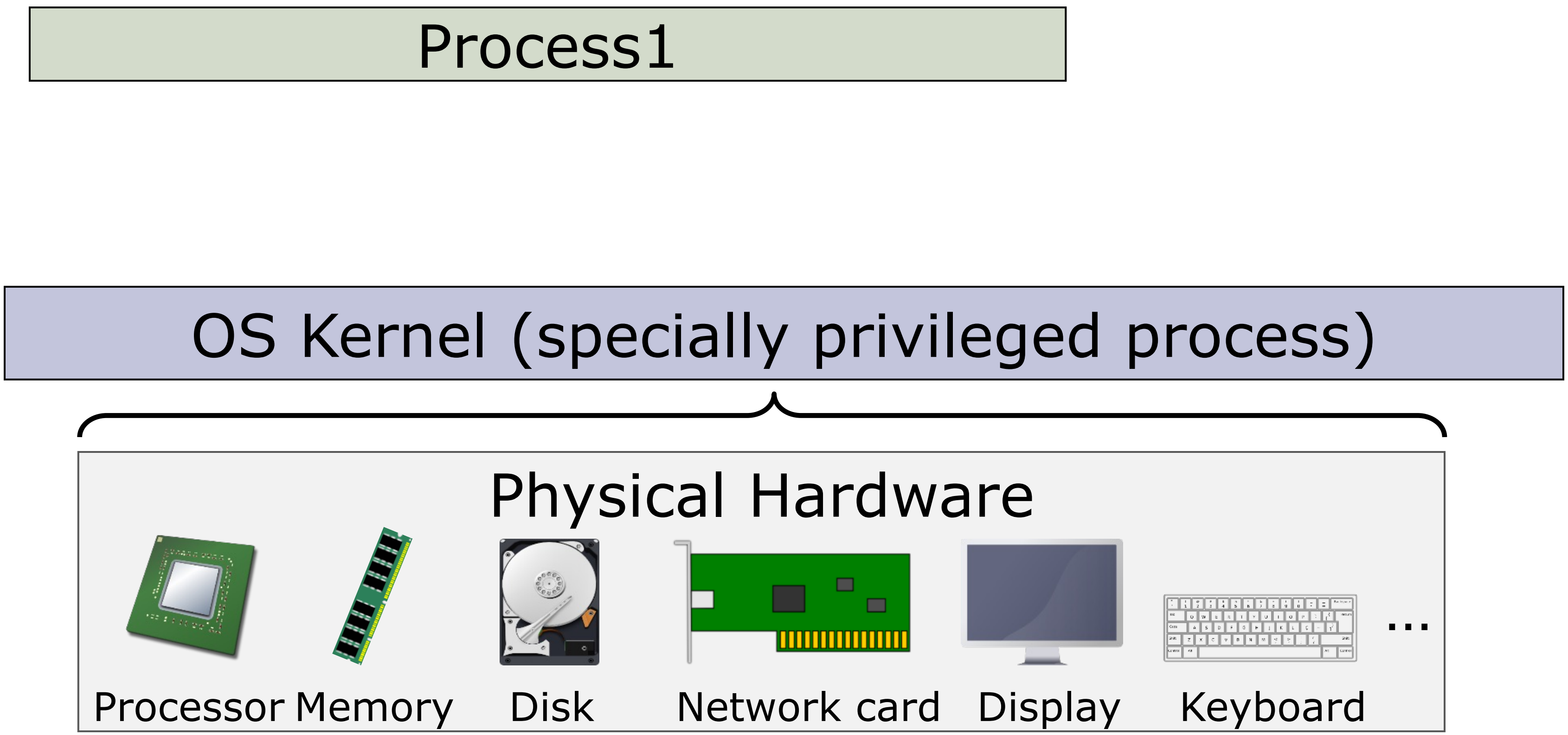

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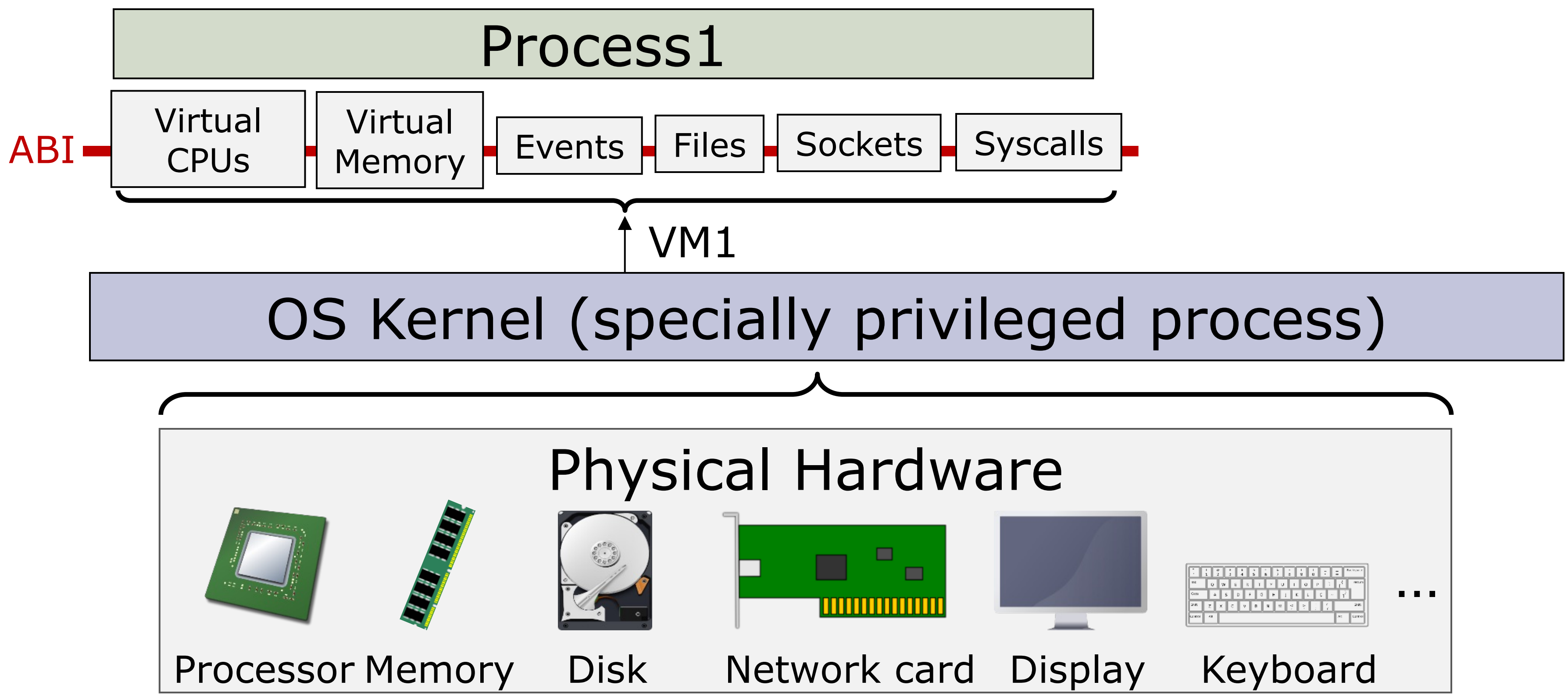

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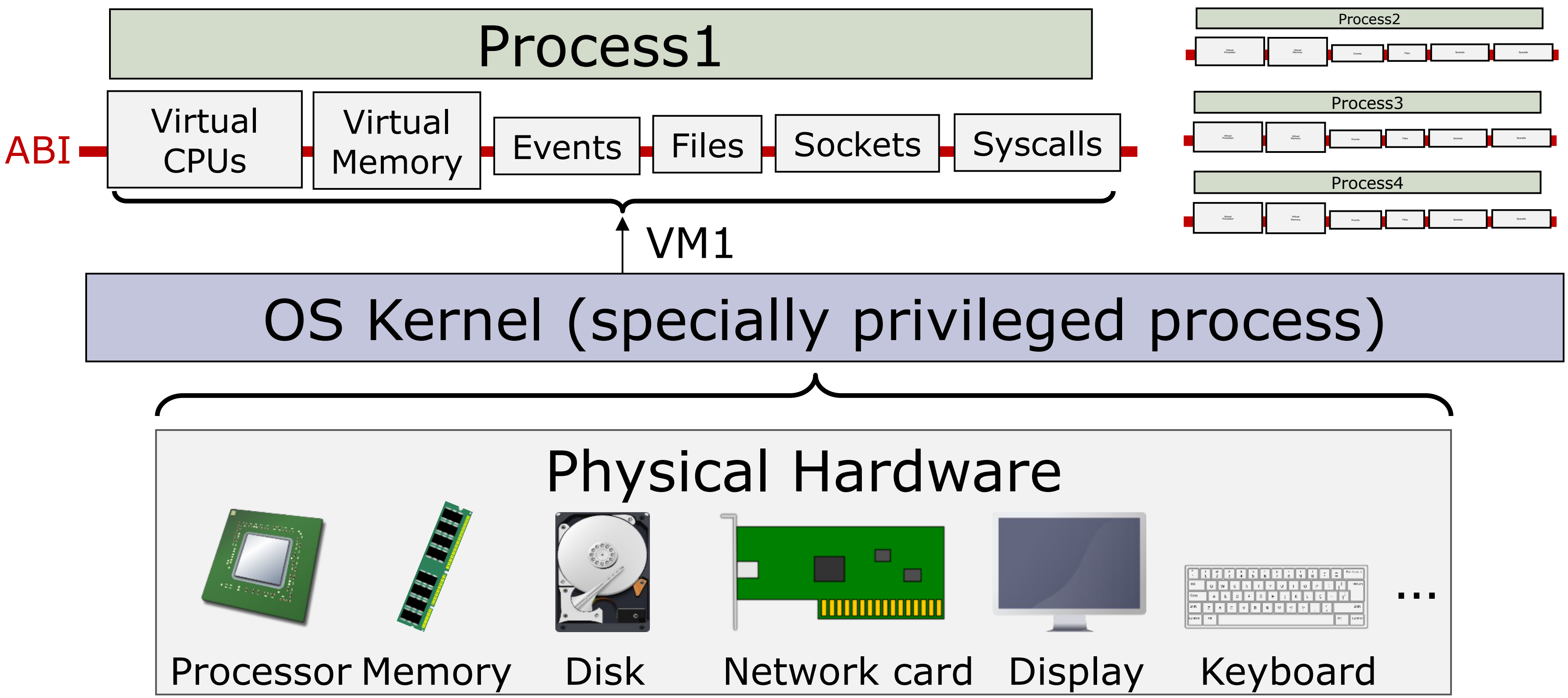
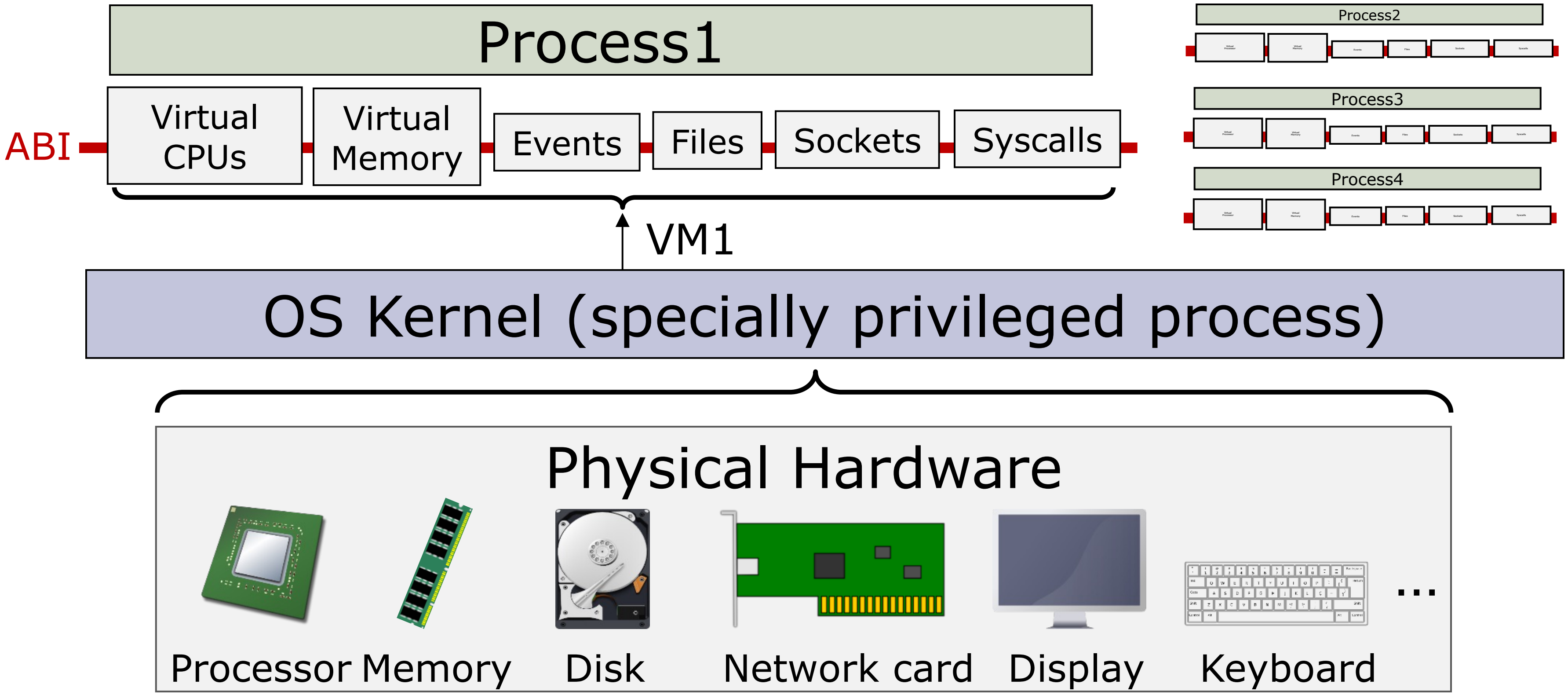


Virtual Machines

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



Virtual Machines Are Everywhere

- Example: Consider a Python program running on a Linux Virtual Machine

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Python program

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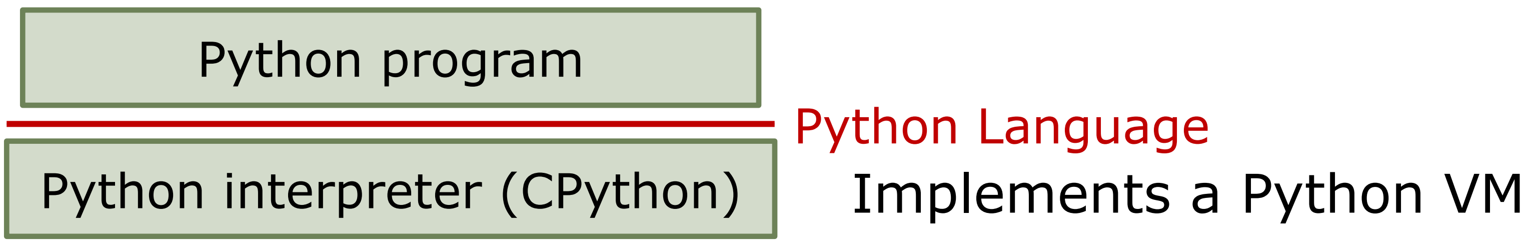

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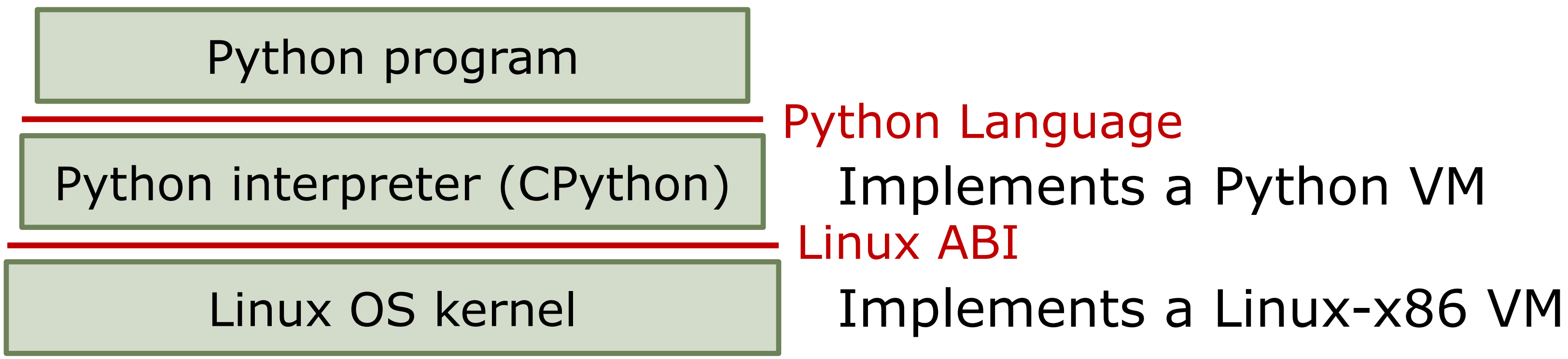

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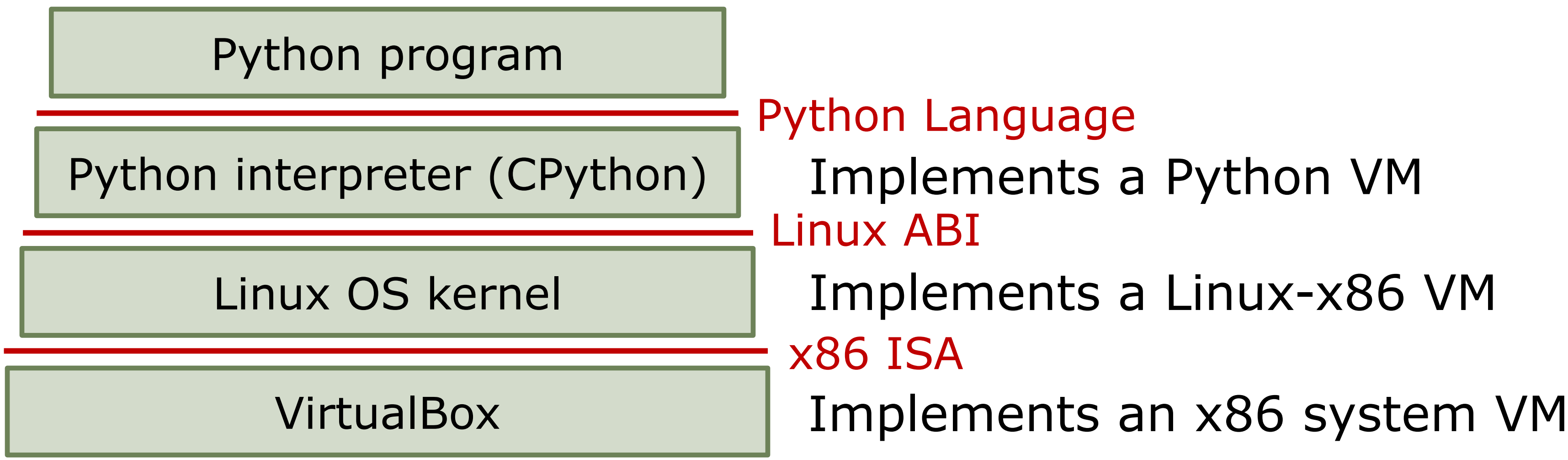

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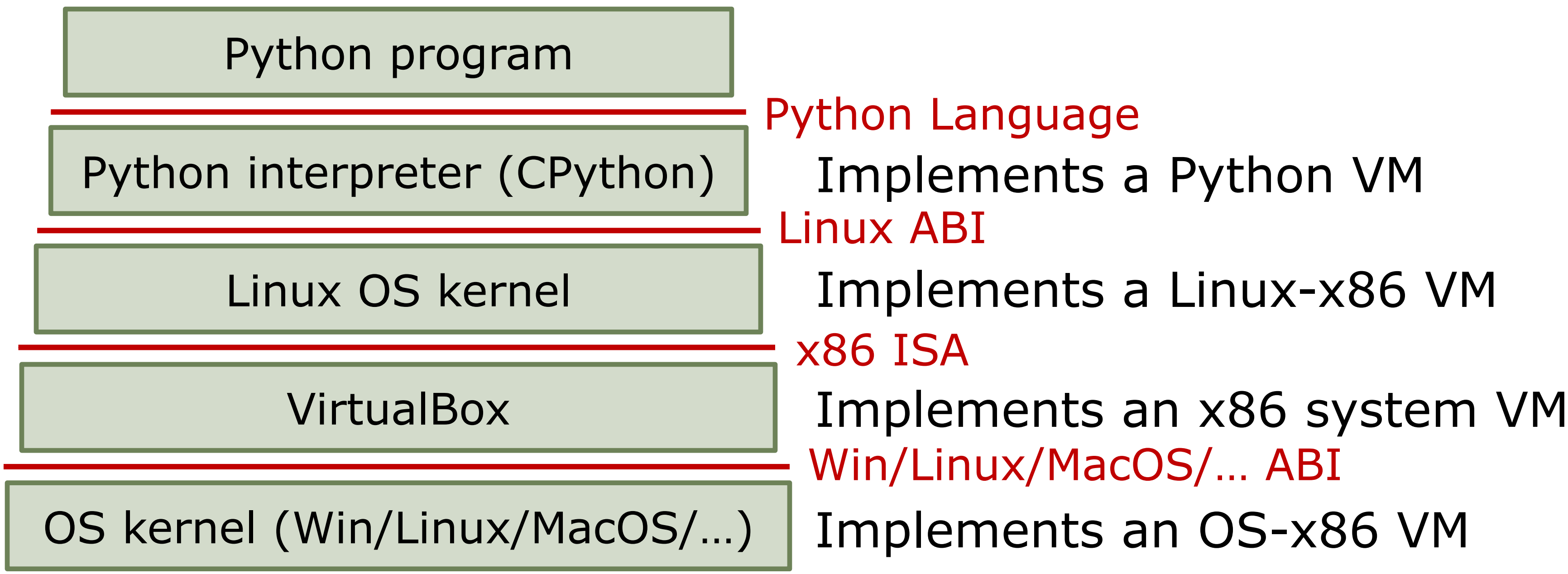

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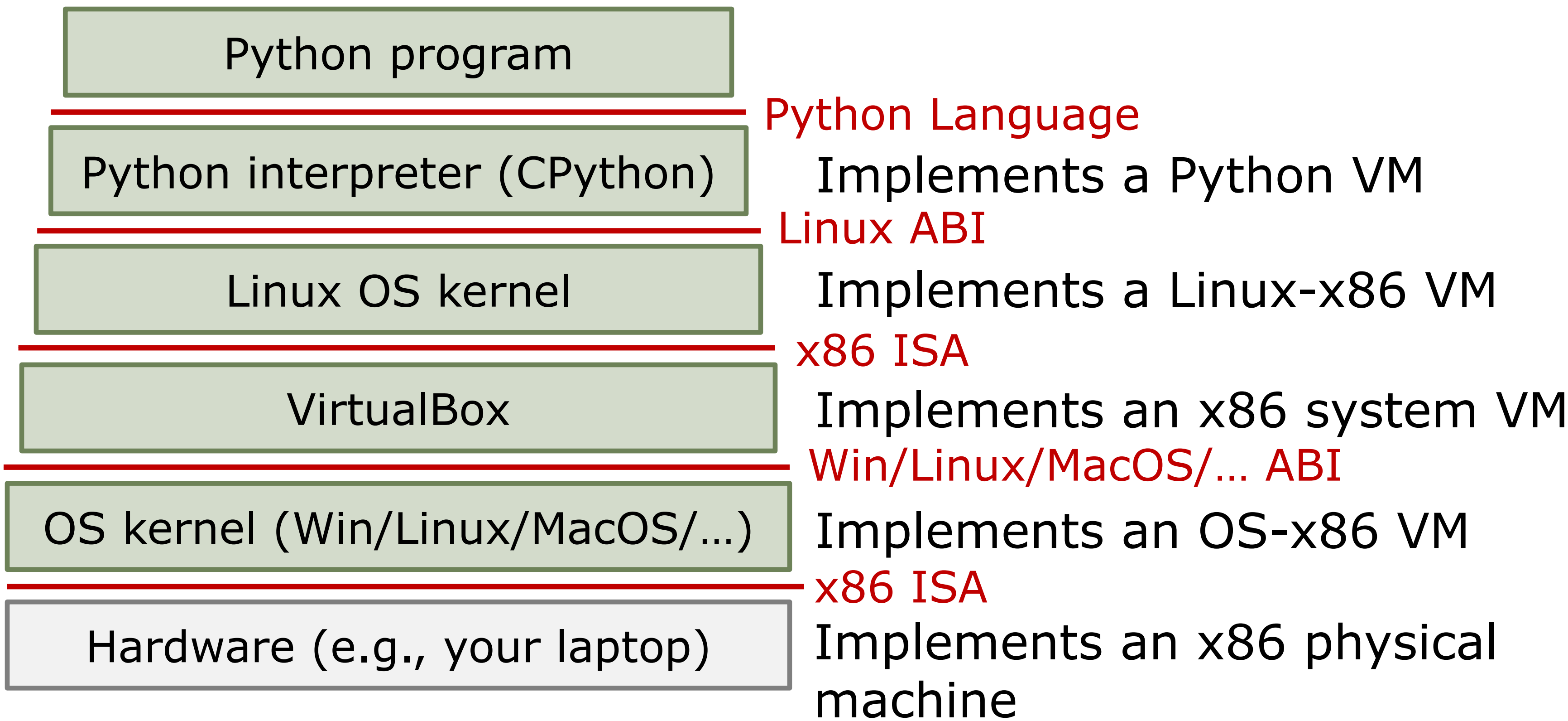

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- We want to support virtual machines with minimal overheads → often need hardware support!

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- 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.

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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

Partial ISA-level virtualization

Implement part of ISA in software to trade-off between performance and cost (make the common things fast):

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- Infrequent but difficult operand values can cause trap
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- 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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Cloud Computing

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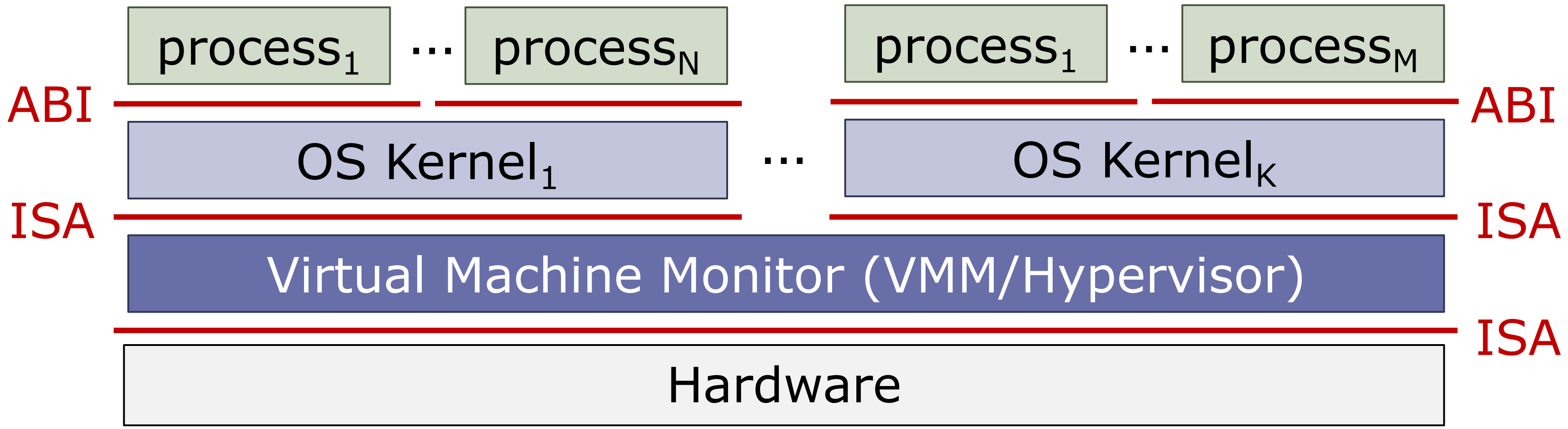
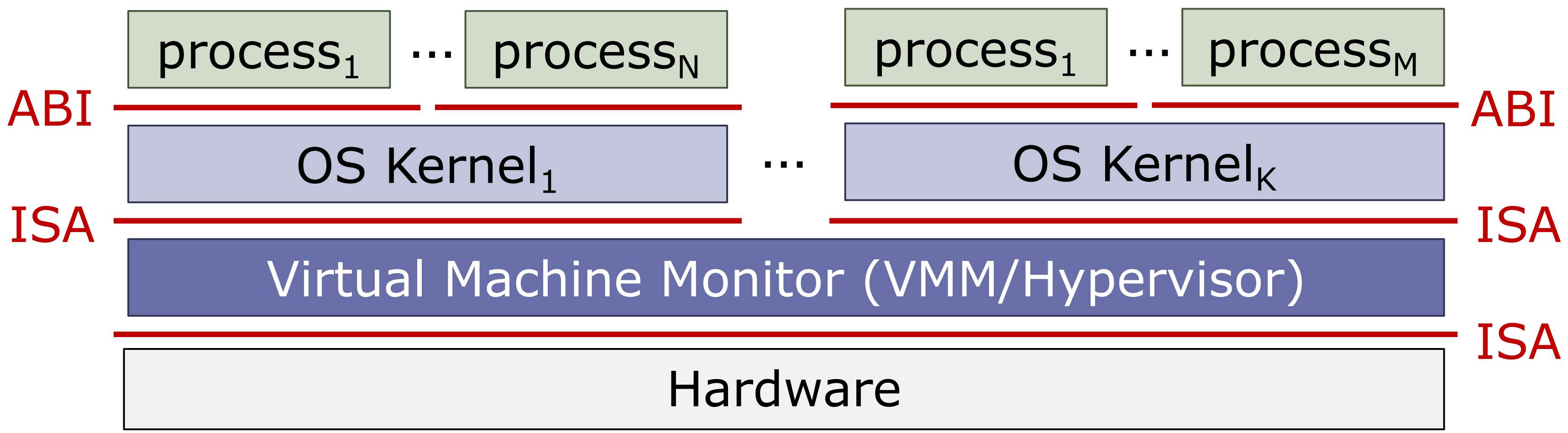
- Allows operating system development without making entire machine unstable or unusable

Cloud Computing

Supporting Multiple OSs



Supporting Multiple OSs



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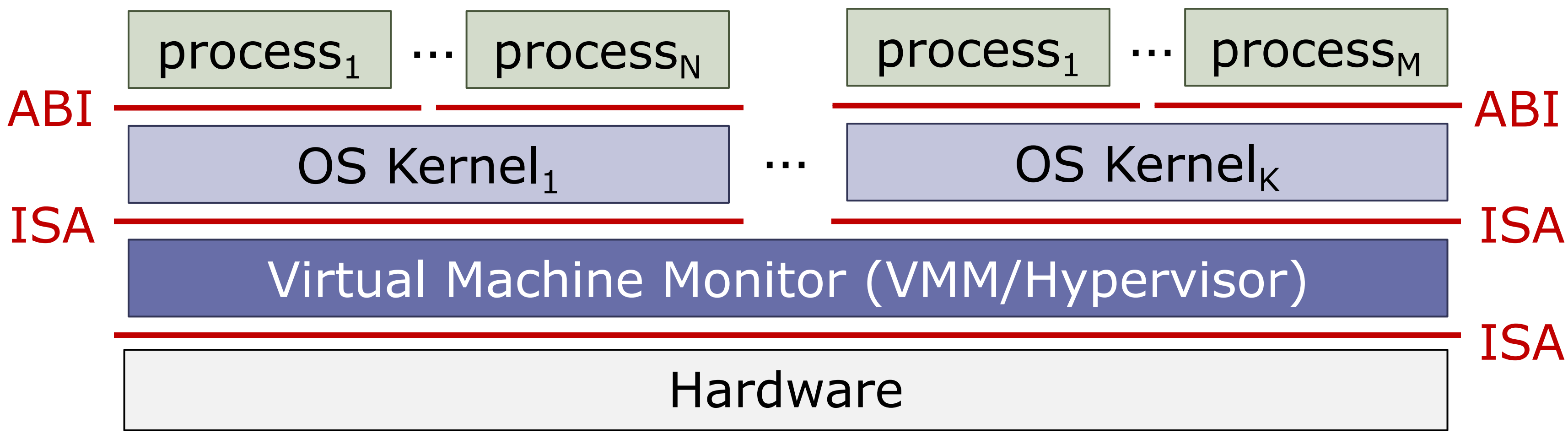


- A VMM (aka Hypervisor) provides a system virtual machine to each OS
- VMM can run directly on hardware (as above) or on another OS
  - Precisely, VMM can be implemented against an ISA (as above) or a process-level ABI. Who knows what lays below the interface…

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. *(previously defined)*

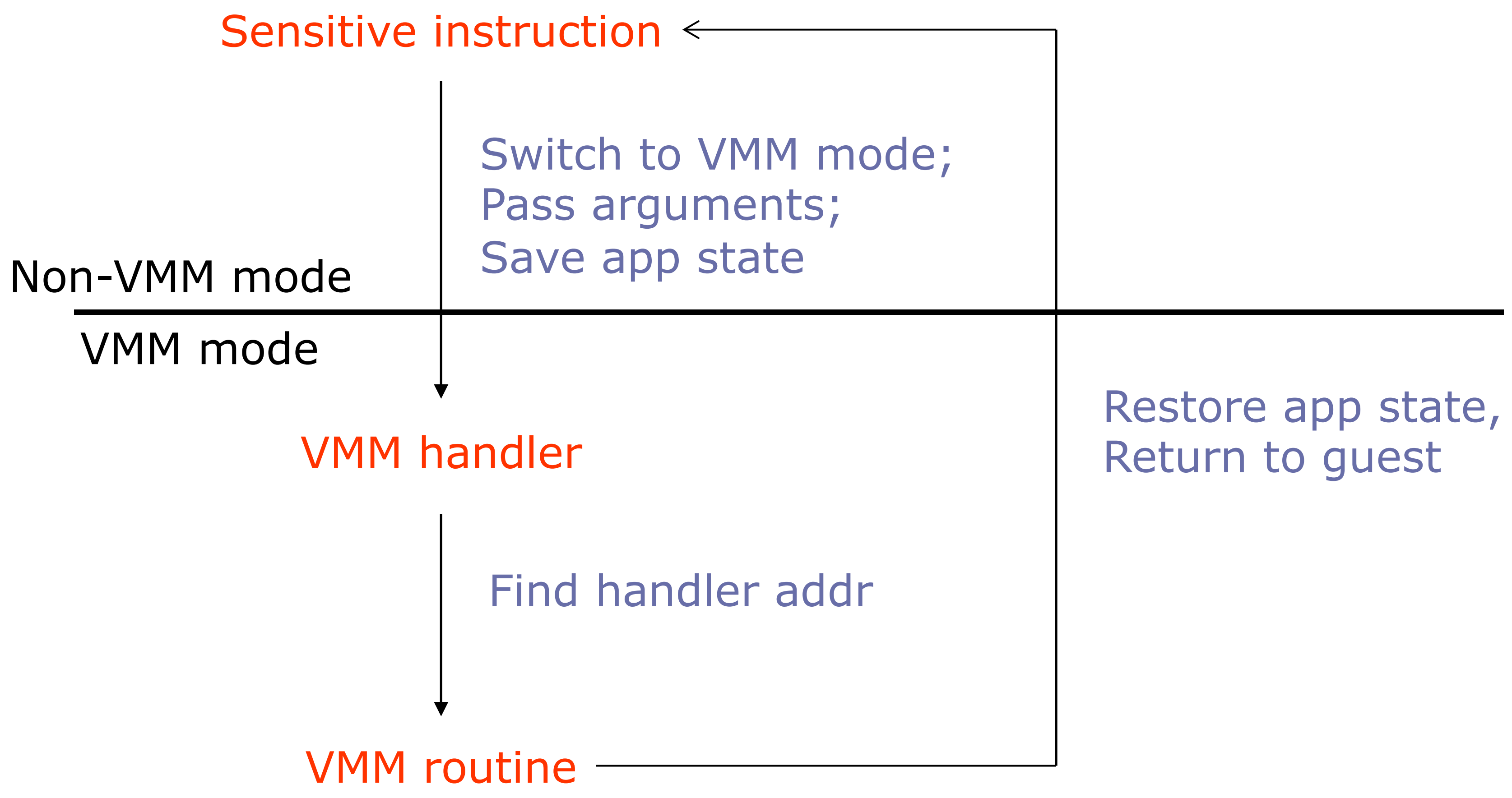
- Control-sensitive instructions: Instructions that attempt to change the configuration of resources in the system.

- Behavior-sensitive instructions: Those whose behavior depends on the configuration of resources, e.g., mode

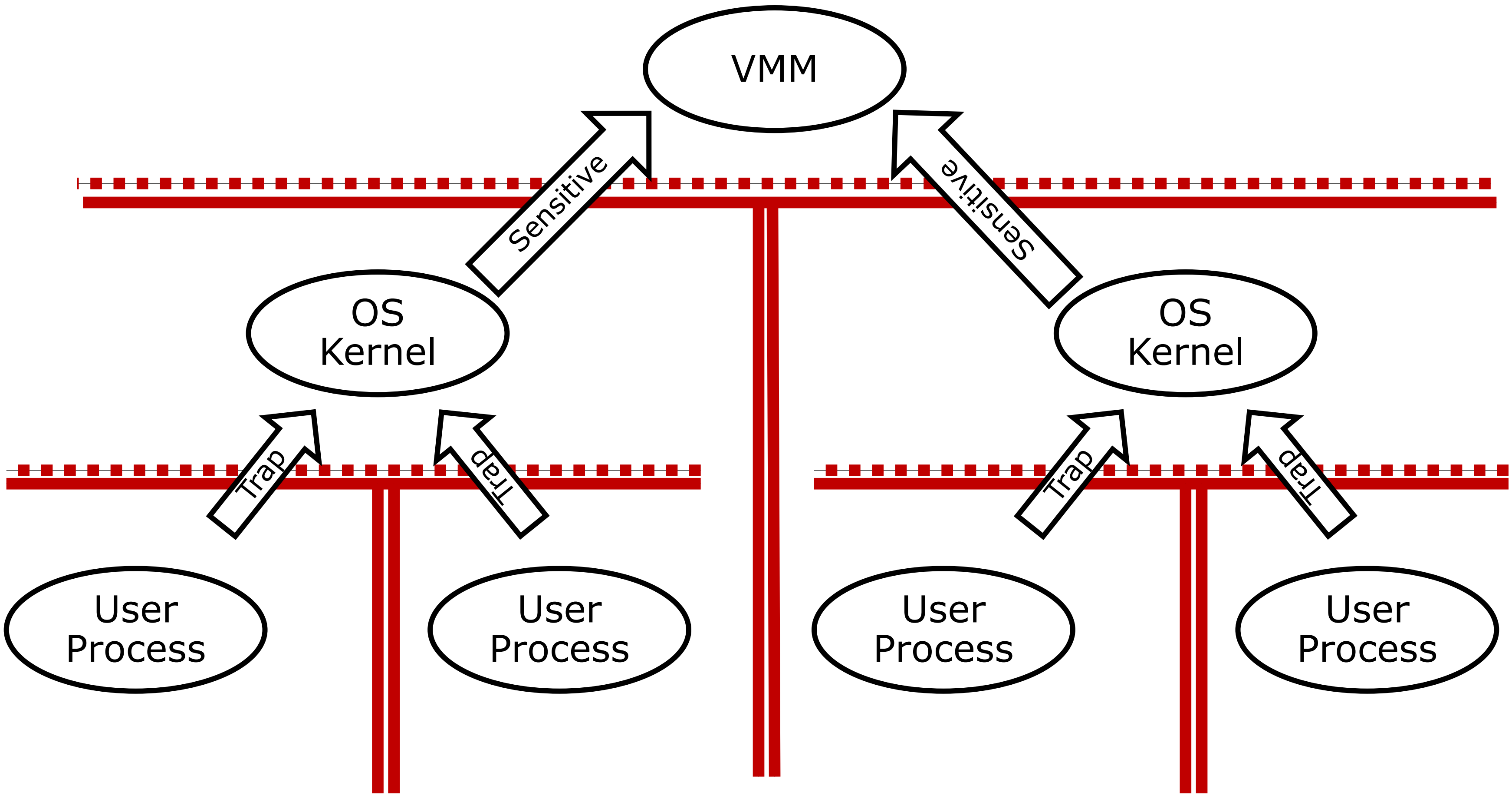
Building an *effective* VMM for an architecture is possible if the set of sensitive instructions is a subset of the set of privileged instructions.

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

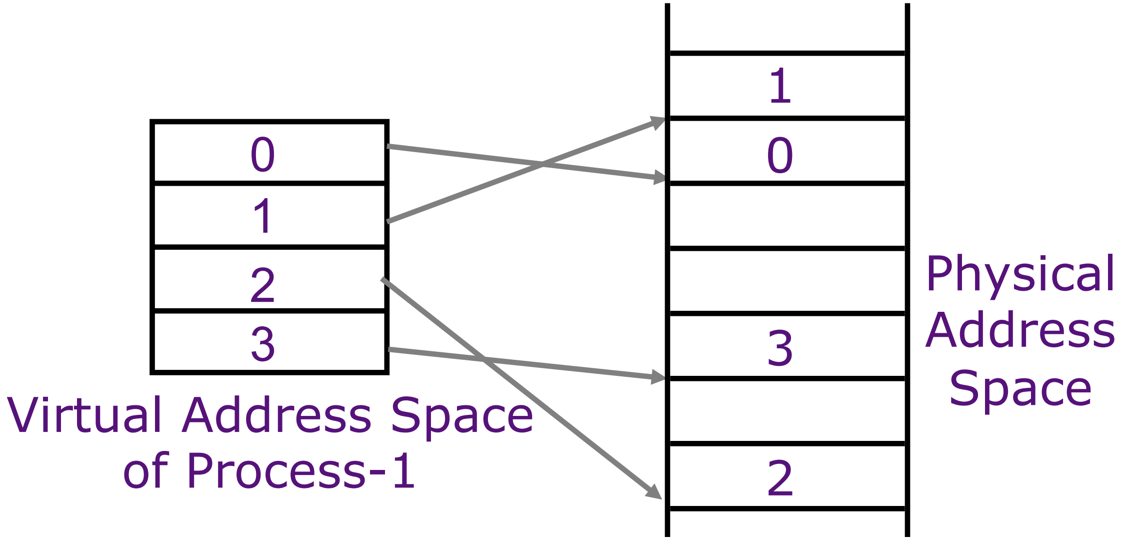
Sensitive instruction handling



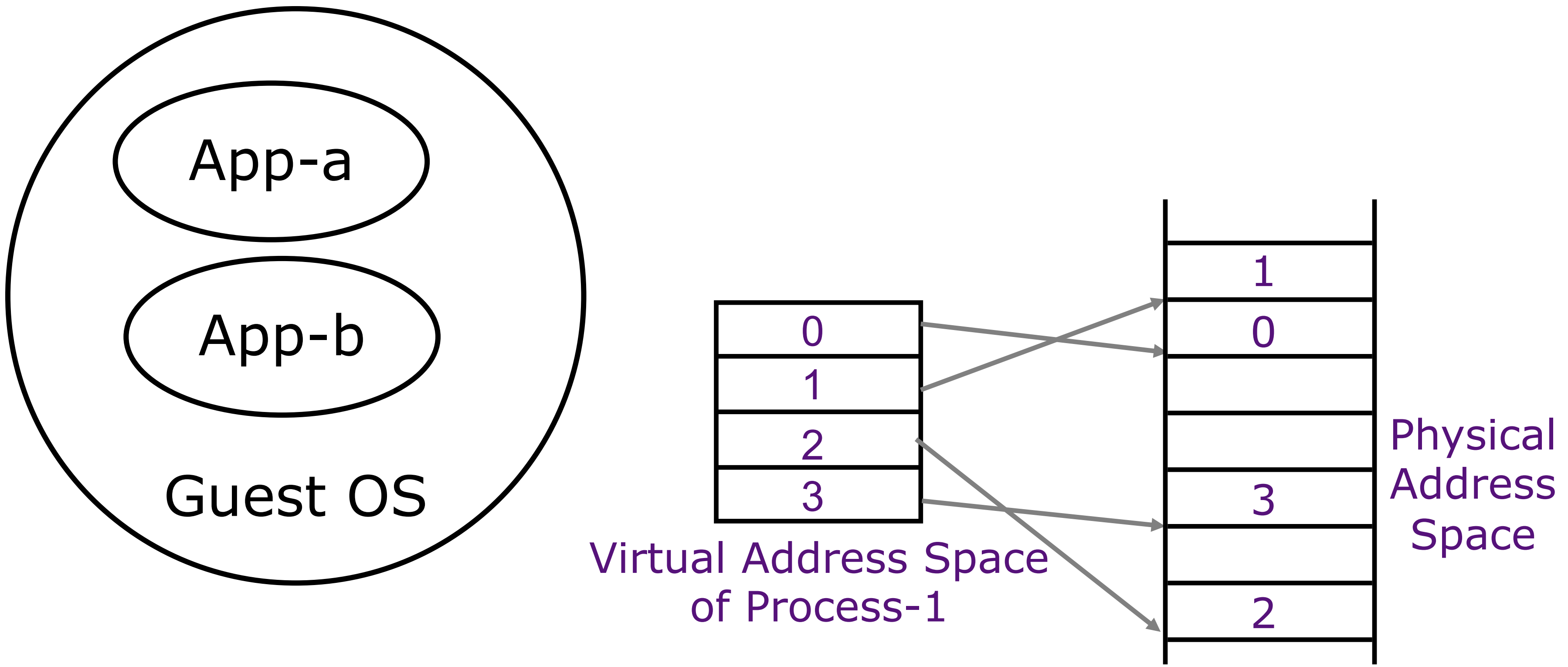
Protection – Multiple OS



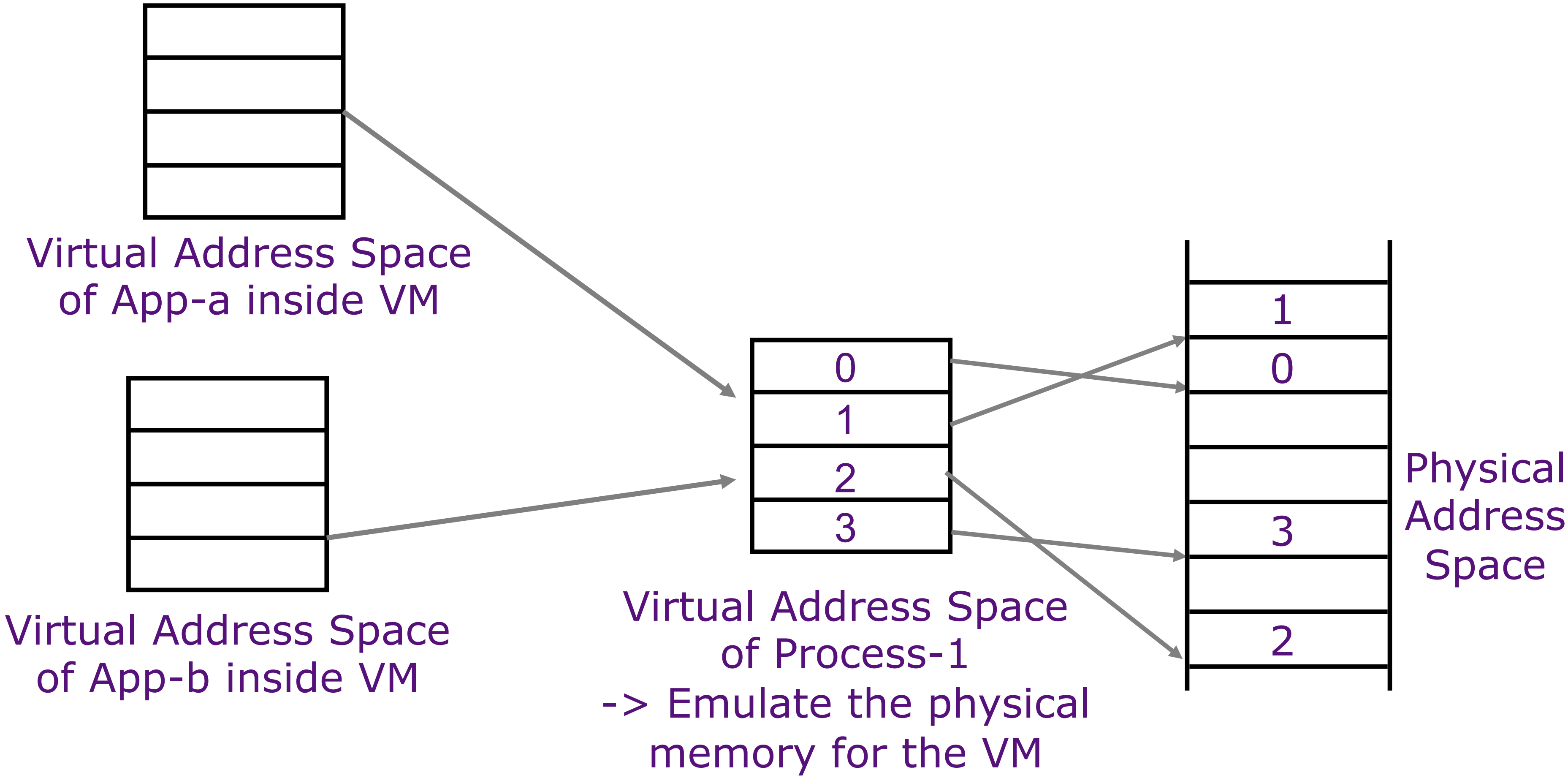
Virtual Memory in VMs



Virtual Memory in VMs

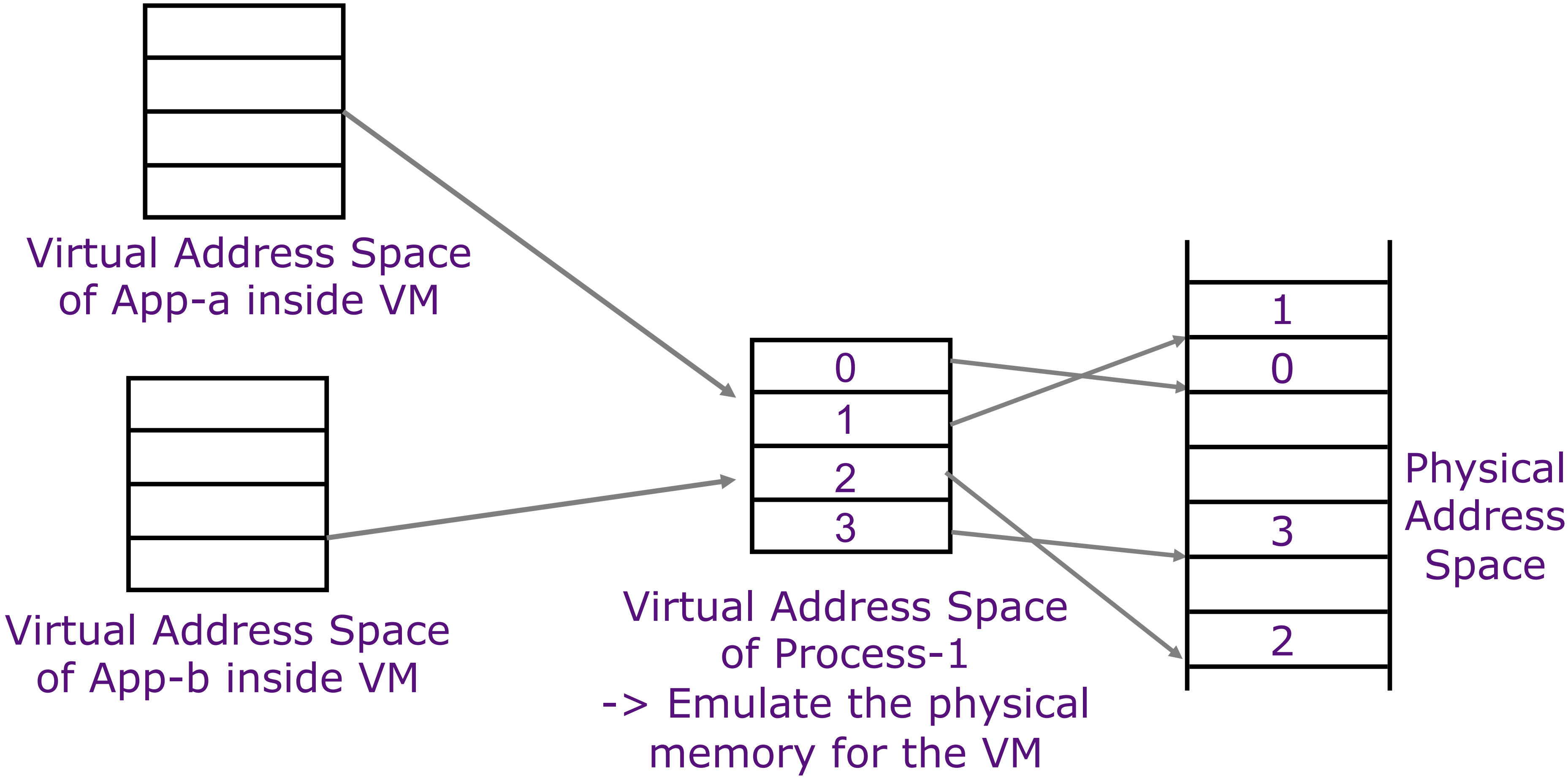


Virtual Memory in VMs

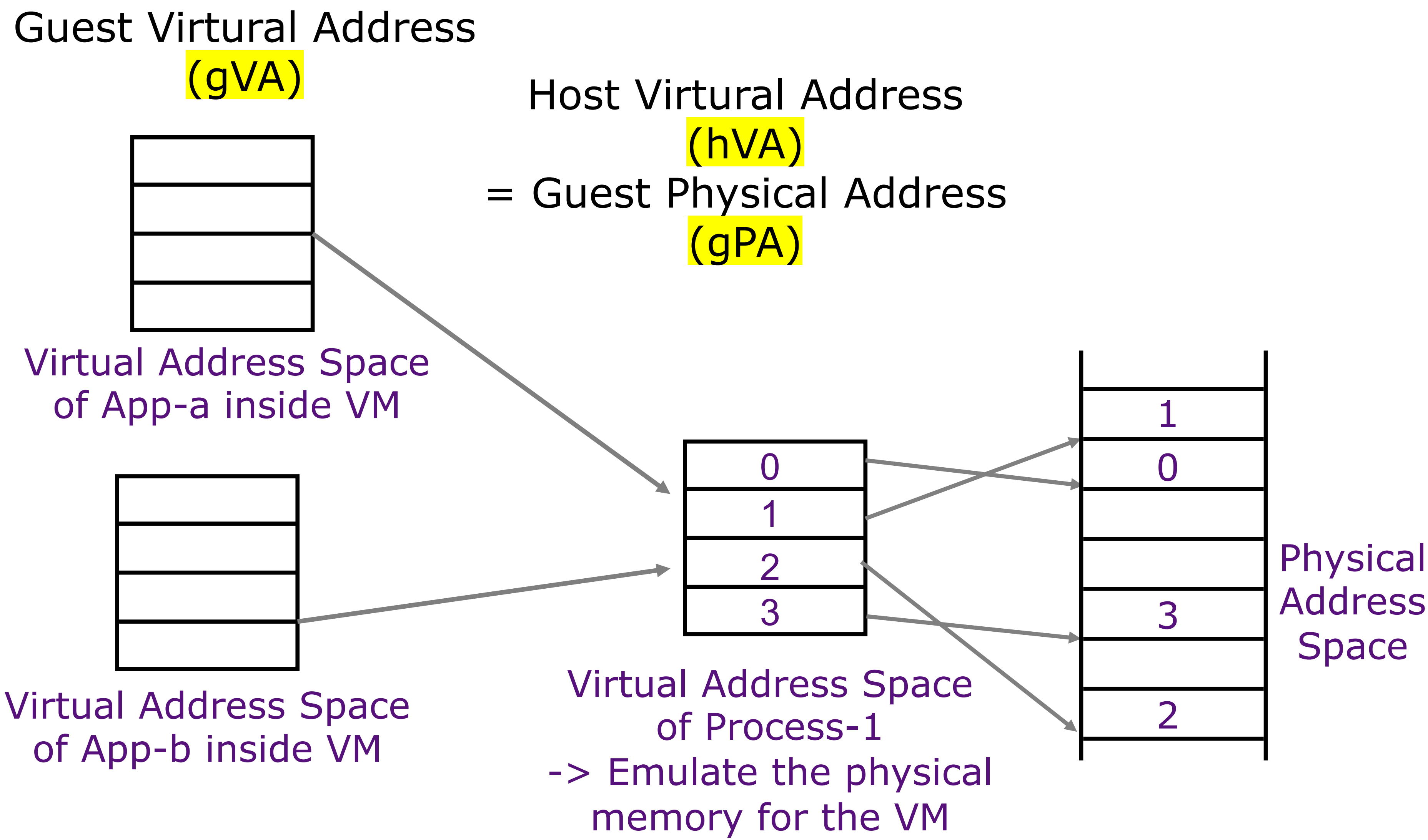


Virtual Memory in VMs

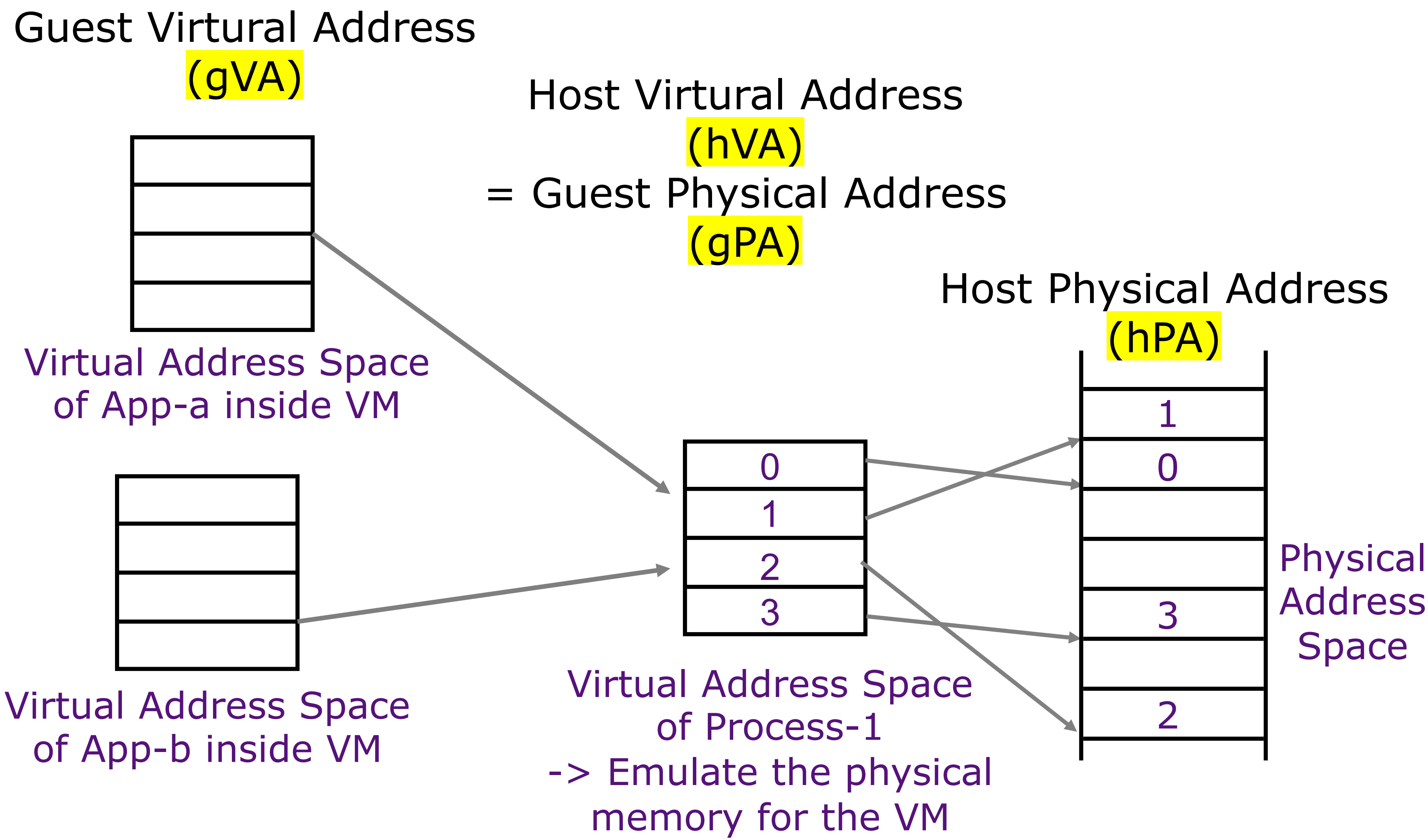
Guest Virtual Address (gVA)



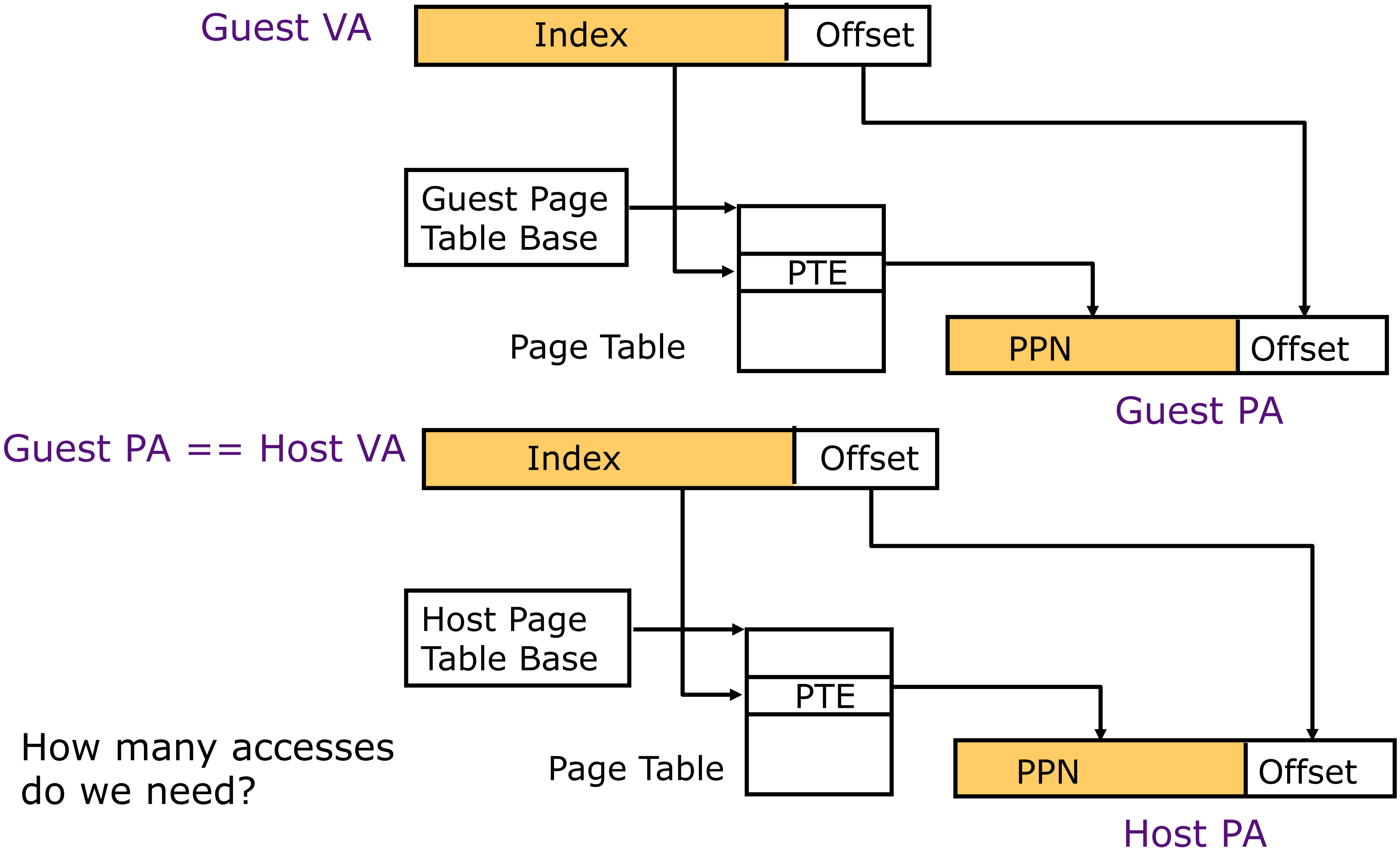
Virtual Memory in VMs



Virtual Memory in VMs

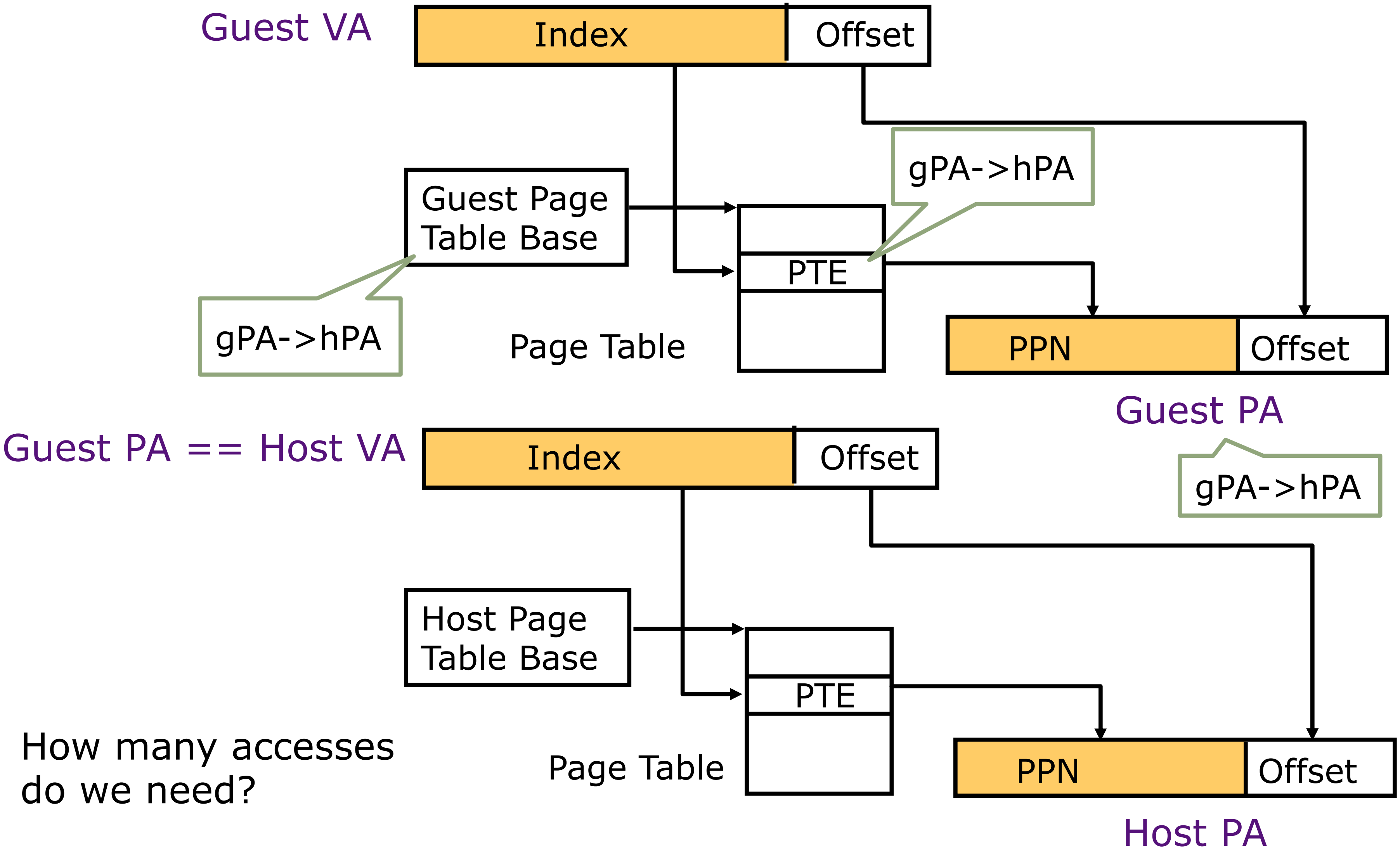


Nested Page Tables



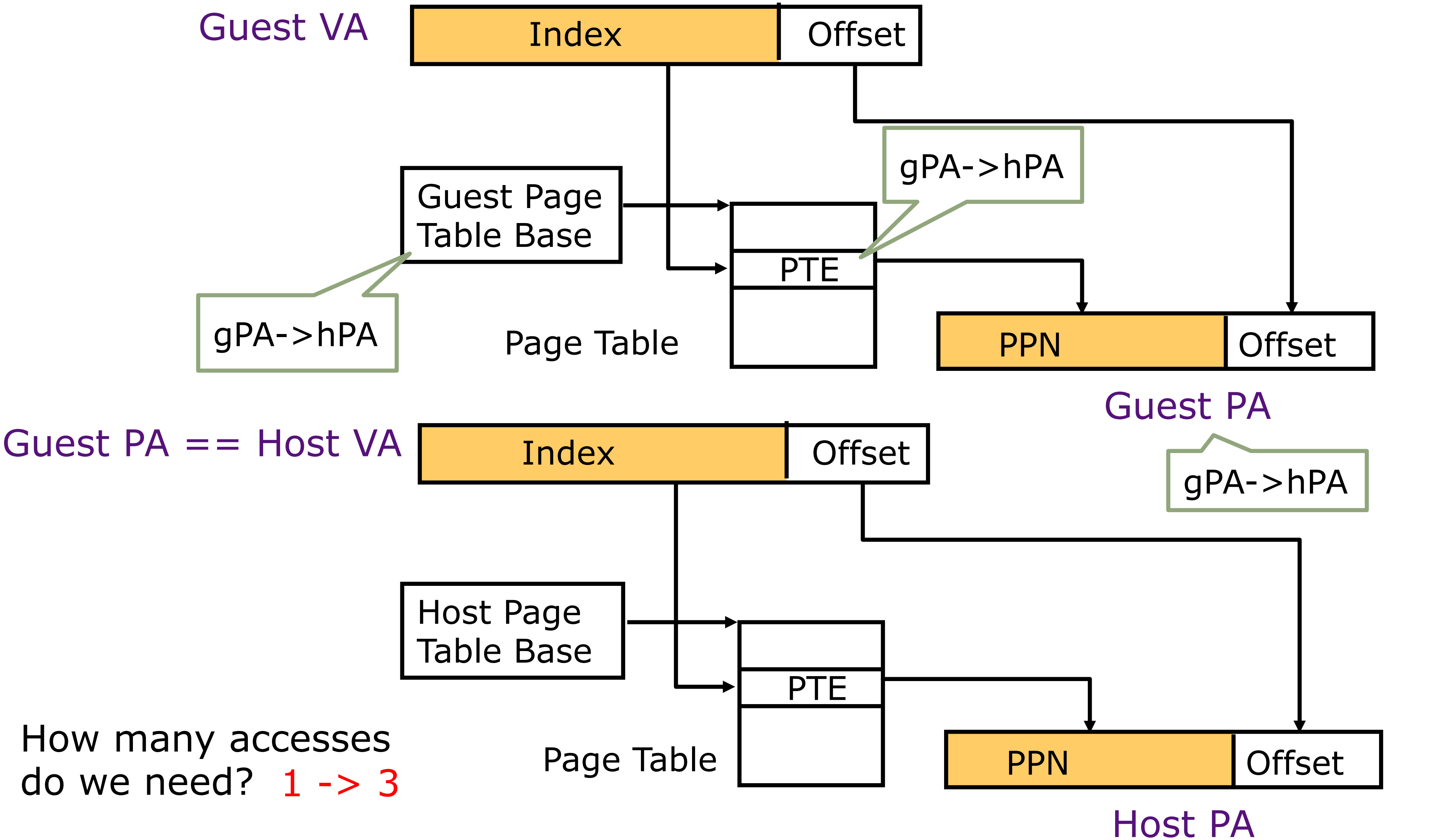
How many accesses do we need?

Nested Page Tables



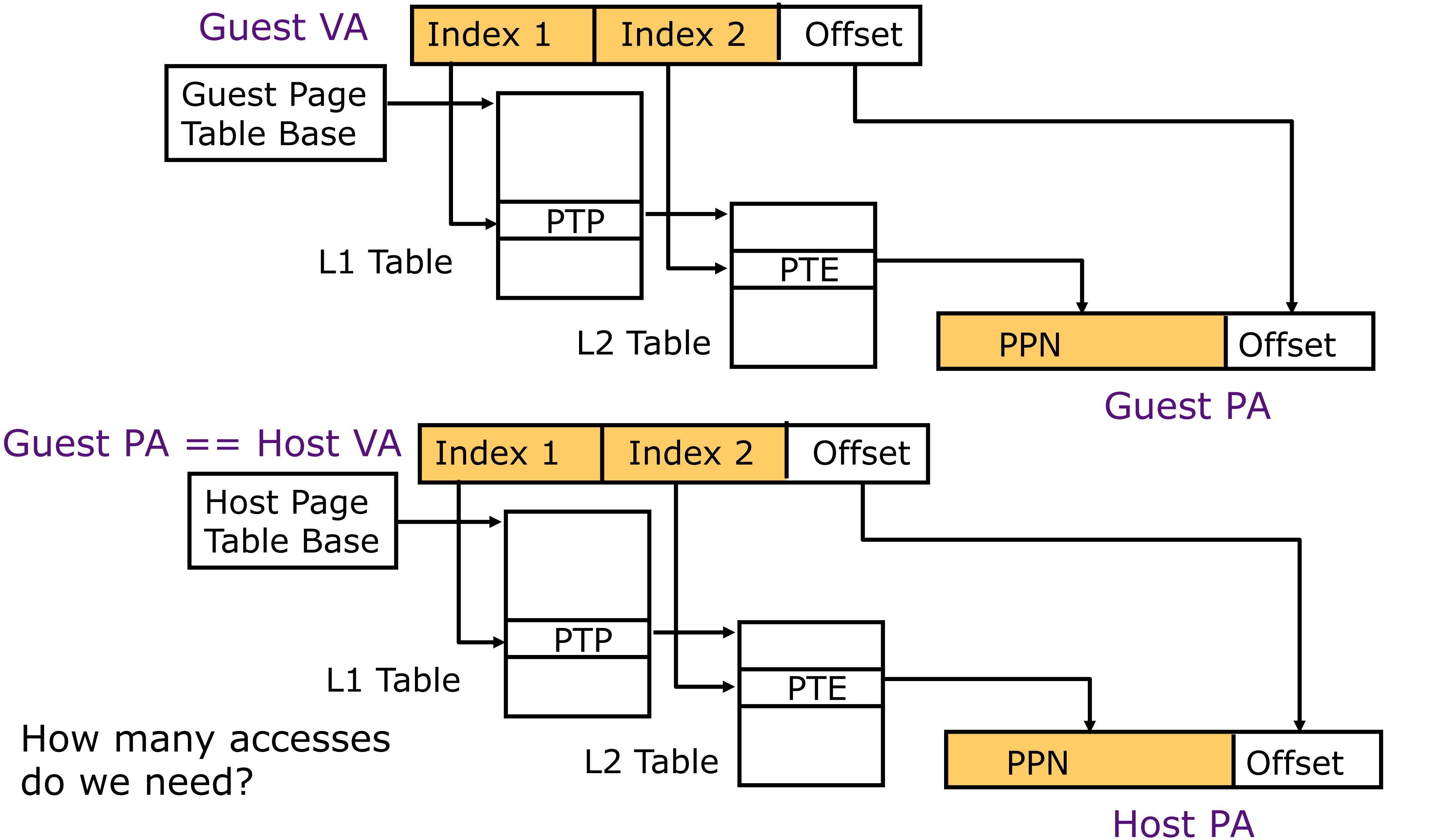
How many accesses do we need?

Nested Page Tables



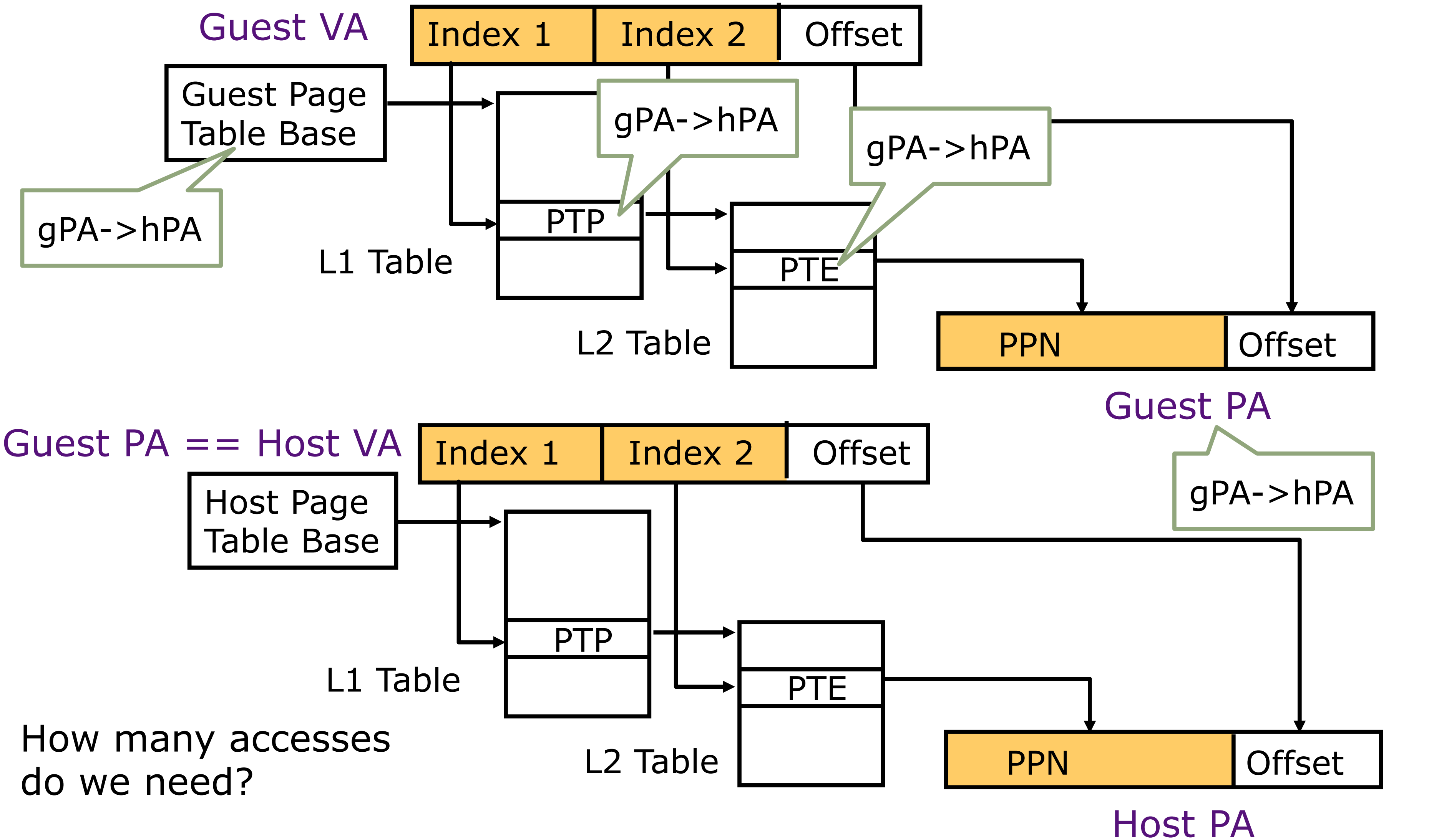
How many accesses do we need? 1 -> 3

Nested Page Tables (Hierarchical)



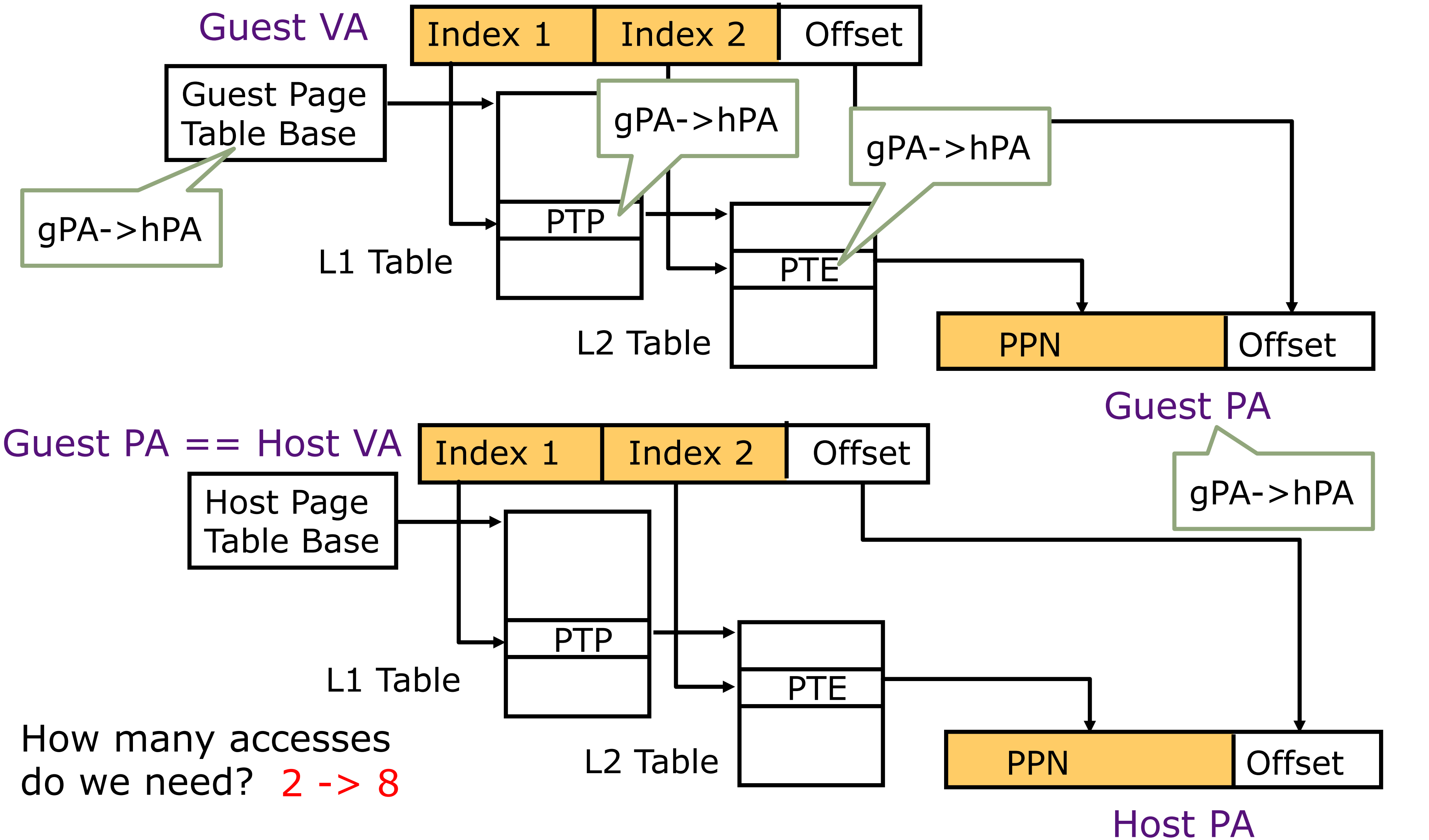
How many accesses do we need?

Nested Page Tables (Hierarchical)



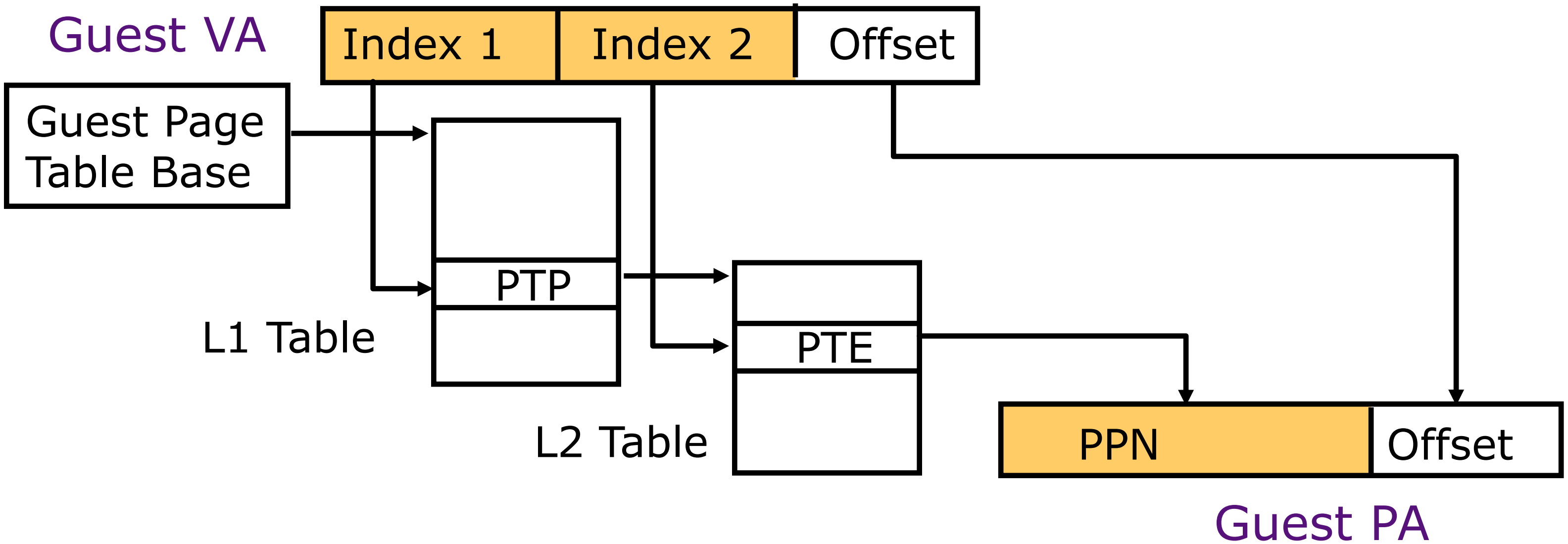
How many accesses do we need?

Nested Page Tables (Hierarchical)



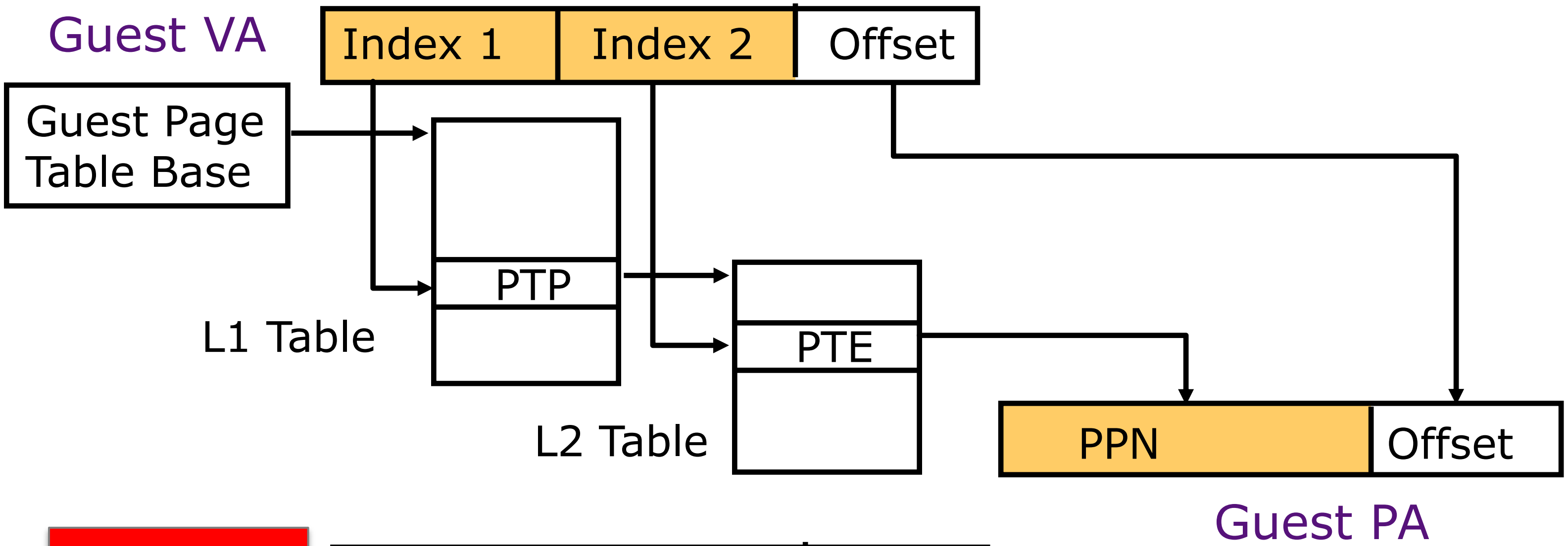
How many accesses do we need? 2 -> 8

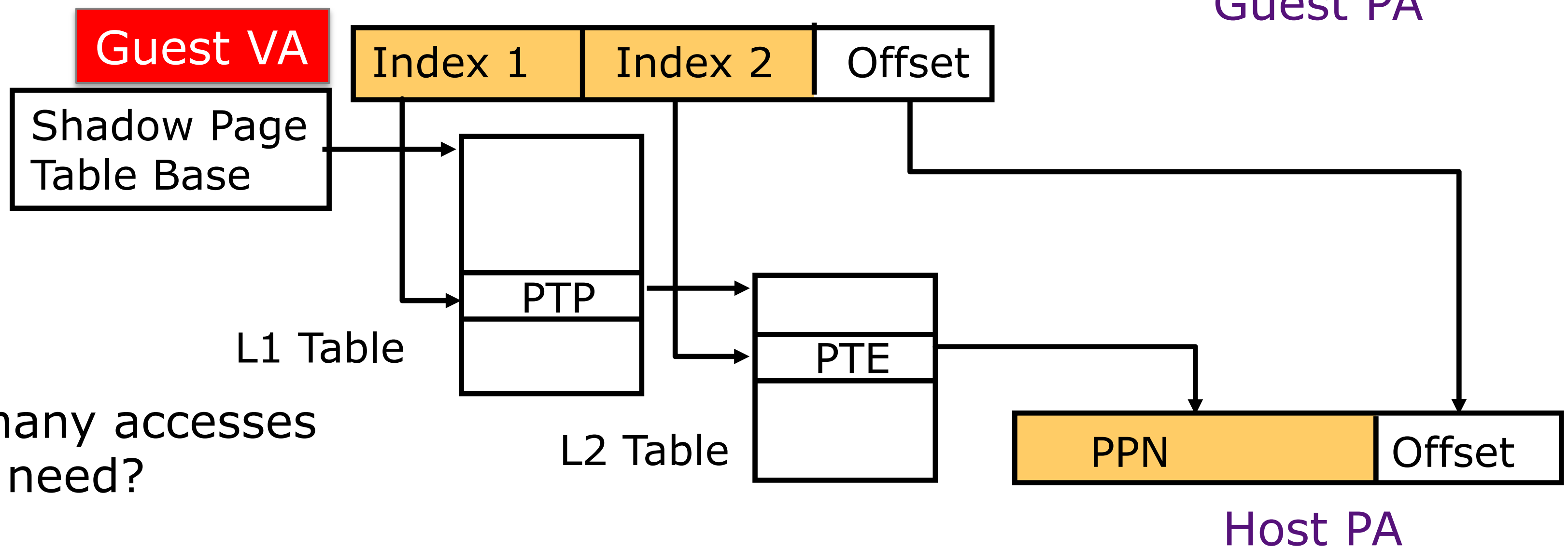
Shadow Page Tables



How many accesses
do we need?

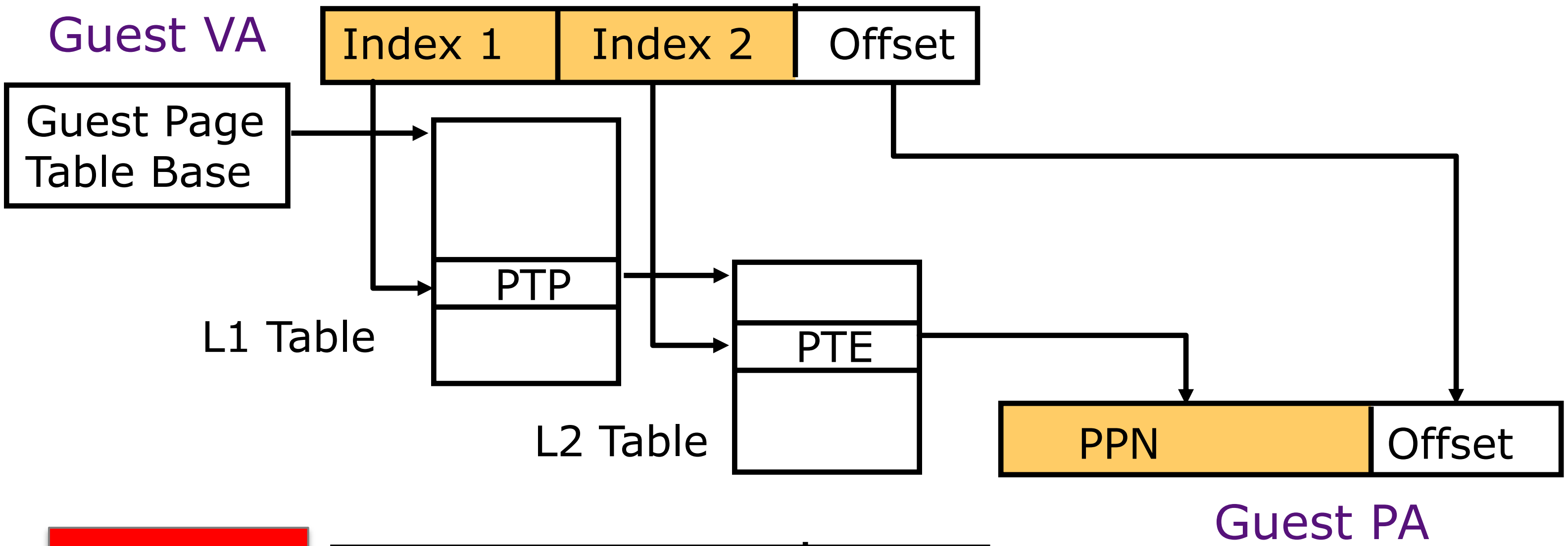
Shadow Page Tables

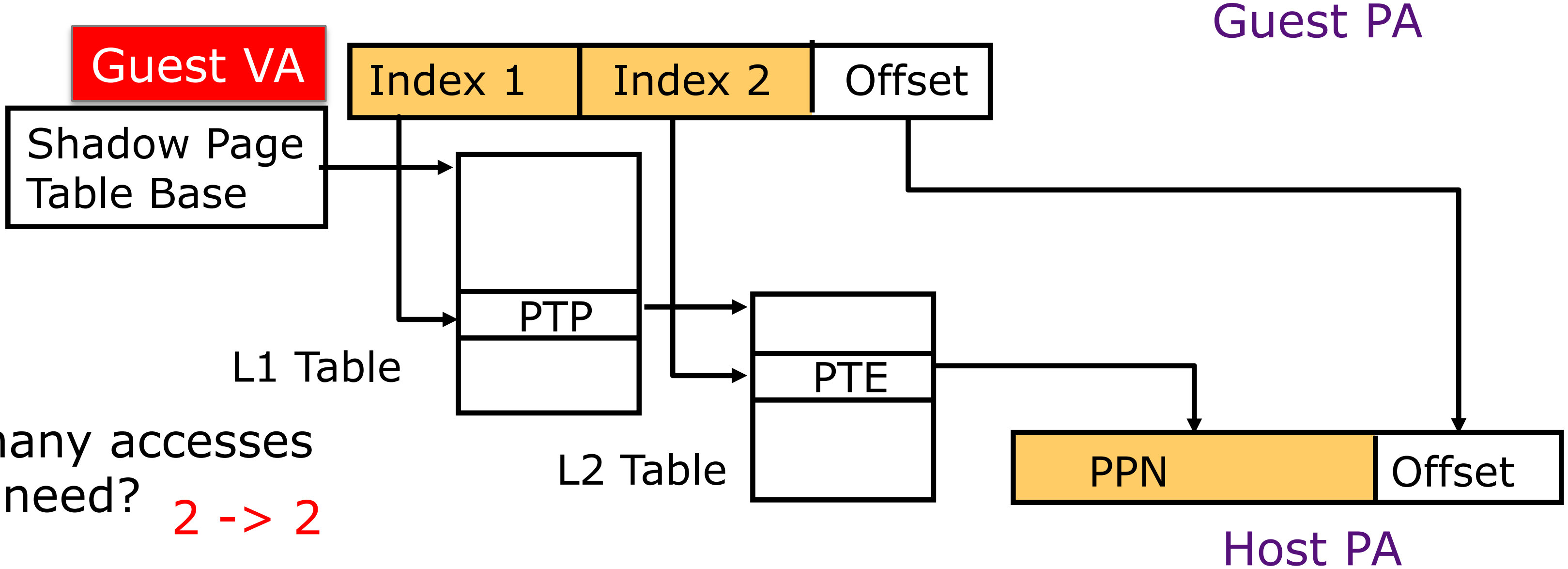




How many accesses do we need?

Shadow Page Tables

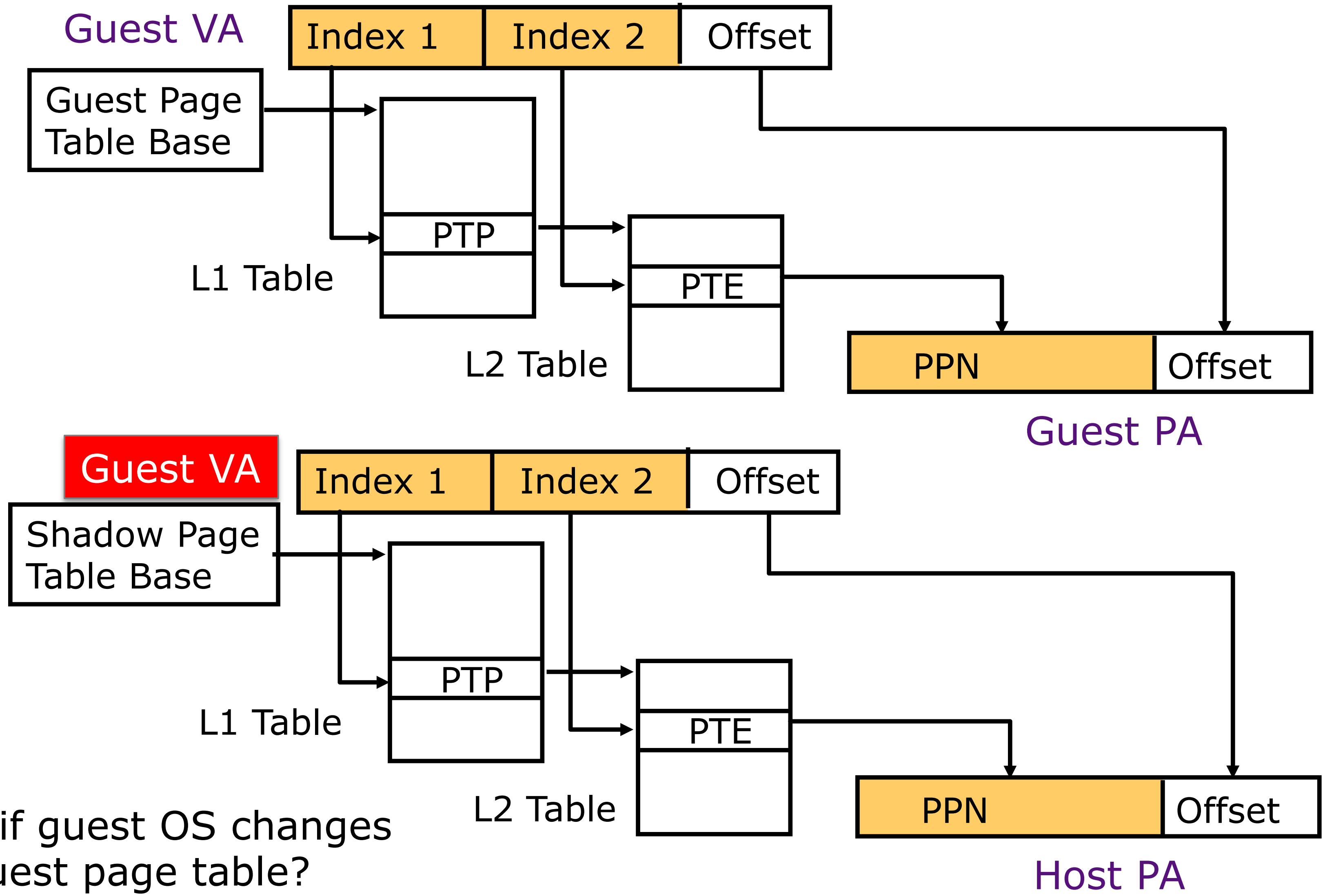




How many accesses do we need?

2 -> 2

Shadow Page Tables



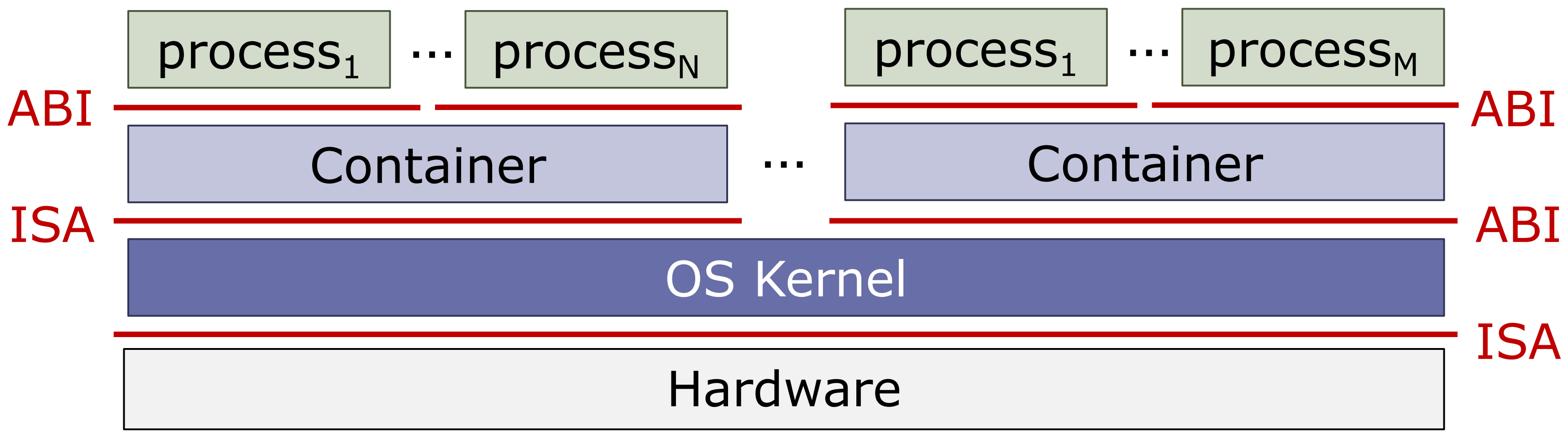
What if guest OS changes the guest page table?

Nested vs Shadow Paging

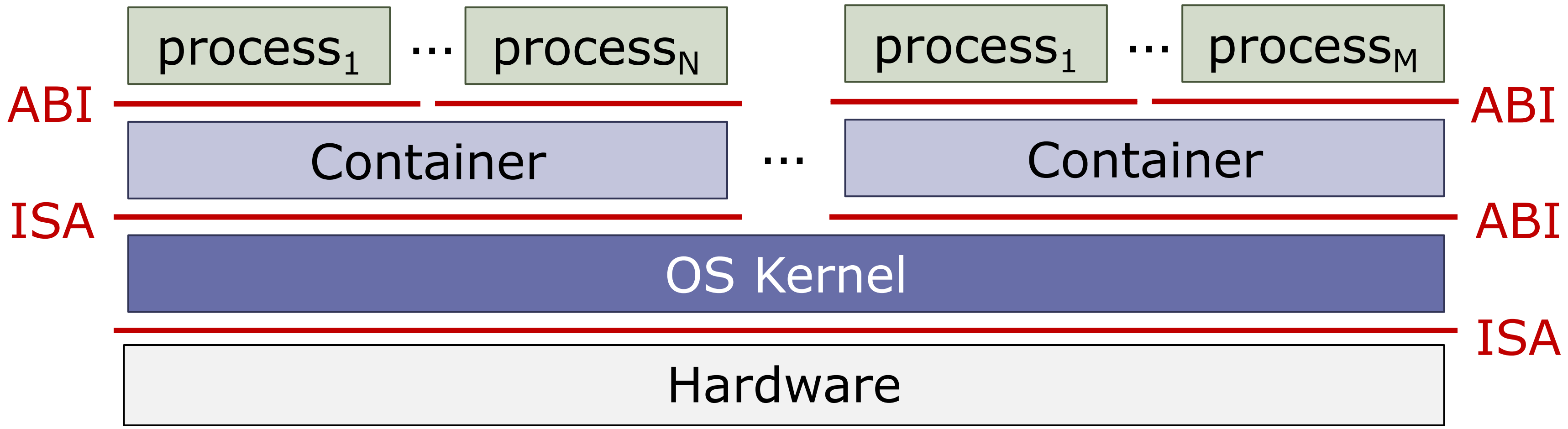
	Native	Nested Paging	Shadow Paging
TLB Hit	VA->PA	gVA->hPA	gVA->hPA
TLB Miss (max)	4	24	4
PTE Updates	Fast	Fast	Uses VMM

On x86-64

Supporting Multiple Process Groups

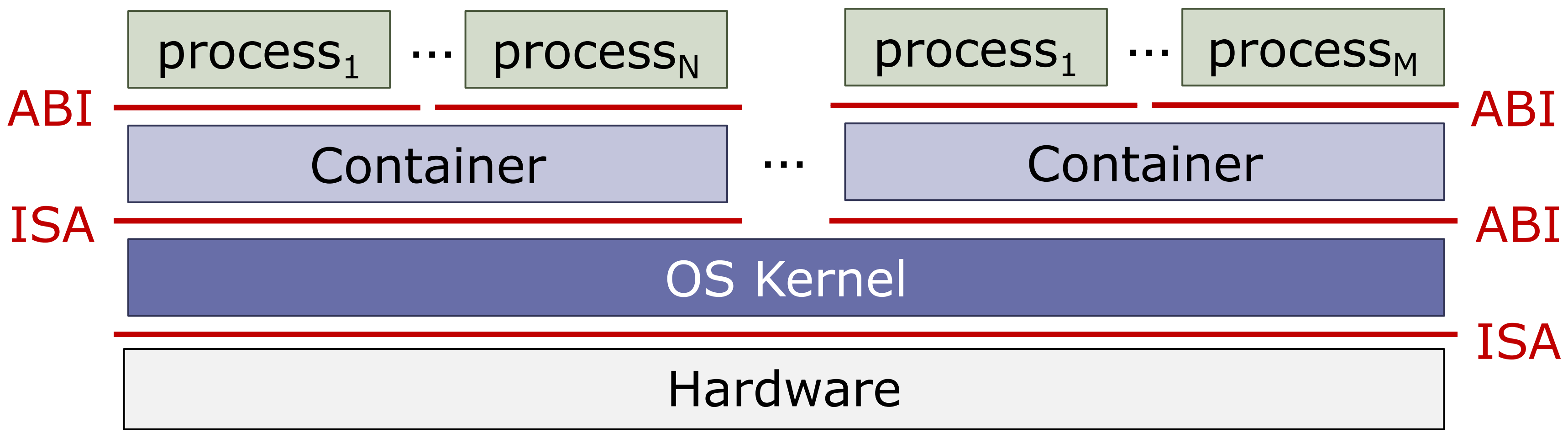


Supporting Multiple Process Groups



- 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

Security and Side Channels

- Hardware isolation mechanisms like virtual memory guarantee that architectural state will not be directly exposed to other processes…and

- ISA and ABI are timing-independent interfaces
  - Specify *what* should happen, not *when*

- …so non-architectural state and other implementation details and timing behaviors (e.g., microarchitectural state, power, etc.) may be used as side channels to leak information!

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: TR1-2:30

Thank you!