Virtualization

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M.I.T.

Evolution in Number of Users

IBM 1620
1959

Single User

Runtime loaded with program

Evolution in Number of Users

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Runtime loaded with program

IBM 360
1960s

Multiple Users

OS for sharing resources

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Evolution in Number of Users

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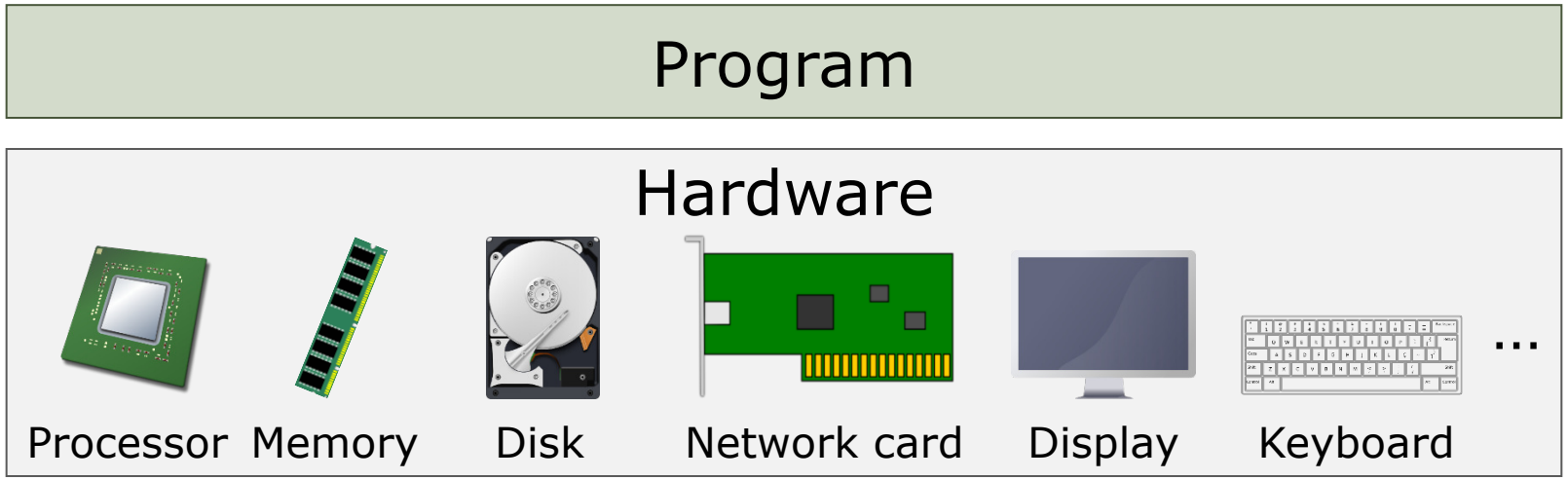
Single User	Multiple Users	Single User	Multiple Users
Runtime loaded with program	OS for sharing resources	OS for sharing resources	Multiple OSs

Single-Program Machine



- Hardware executes a single program and has direct and complete access to all hardware resources

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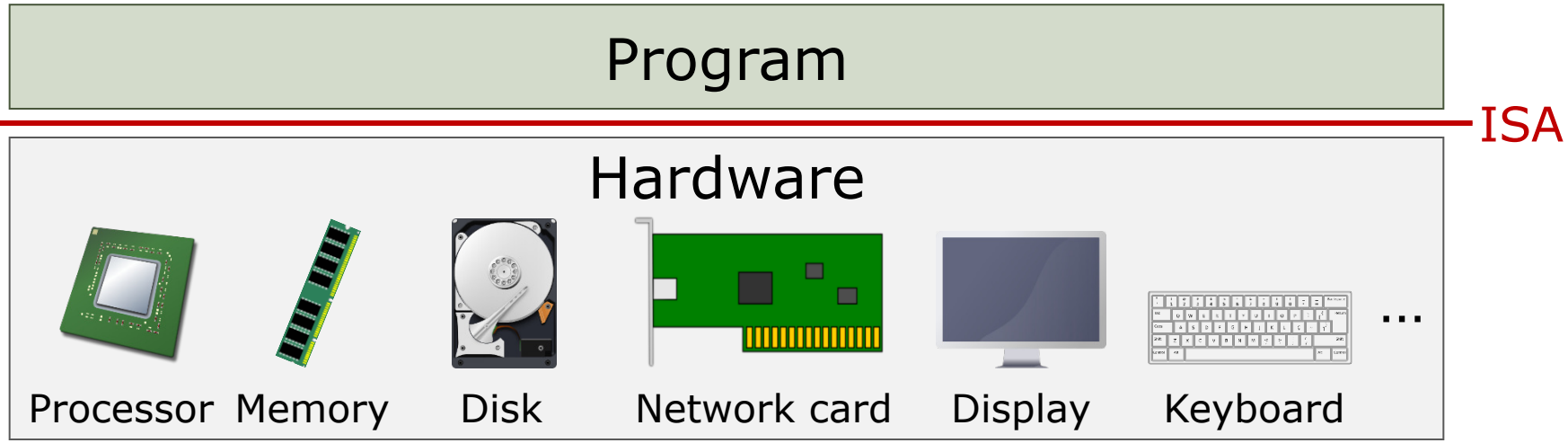

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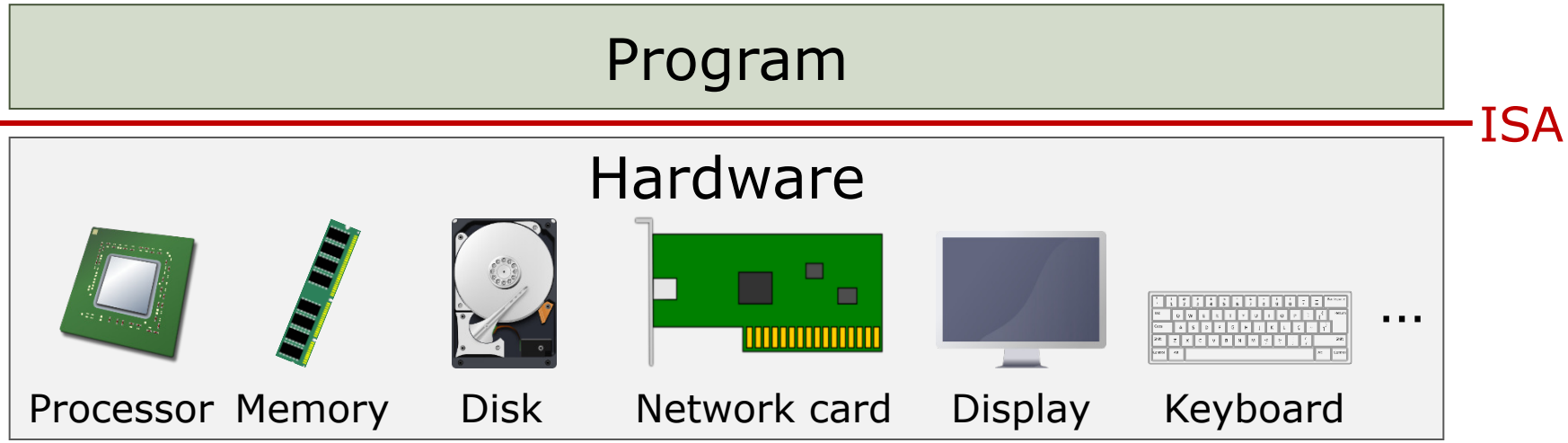

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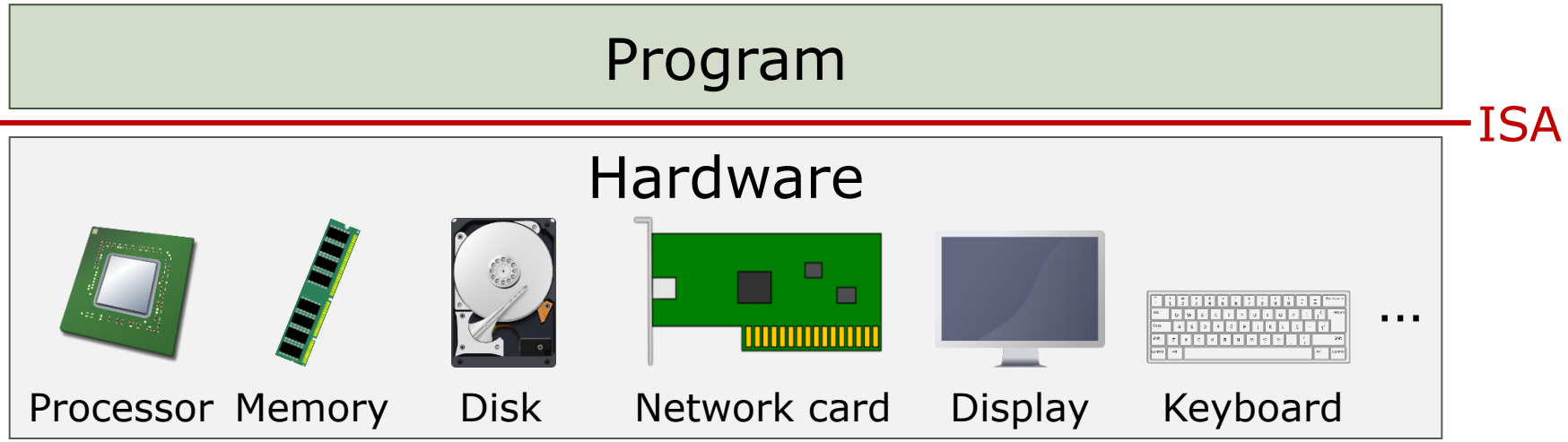

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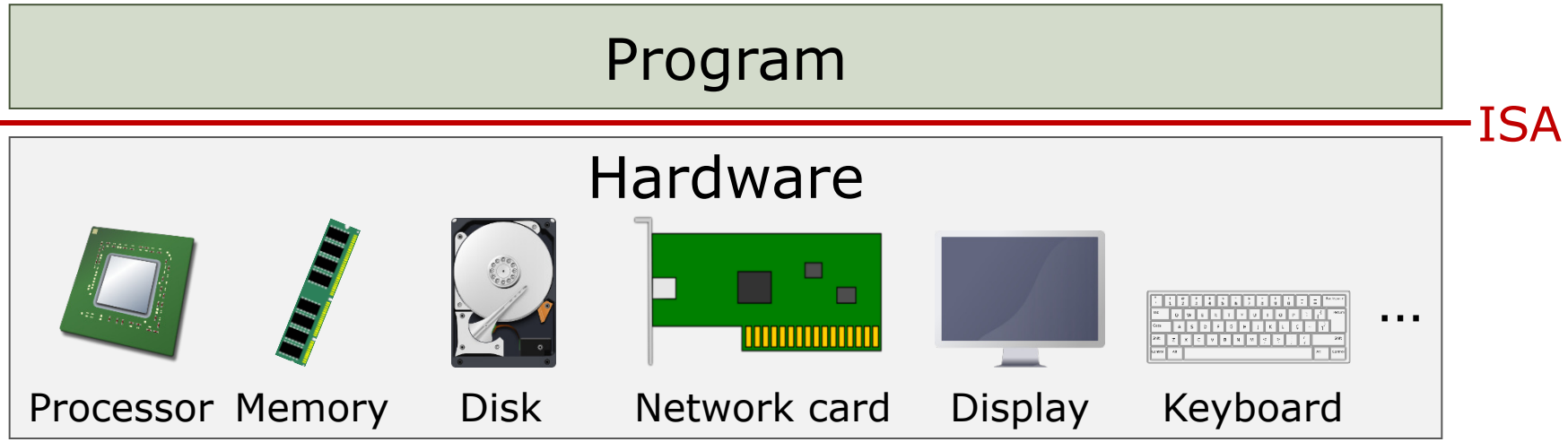

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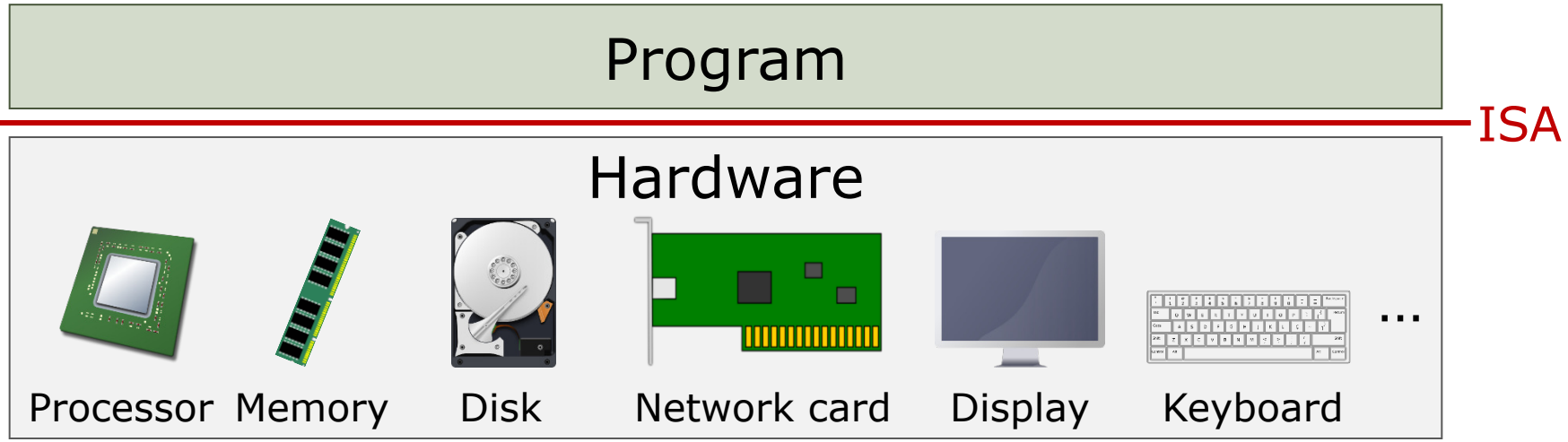

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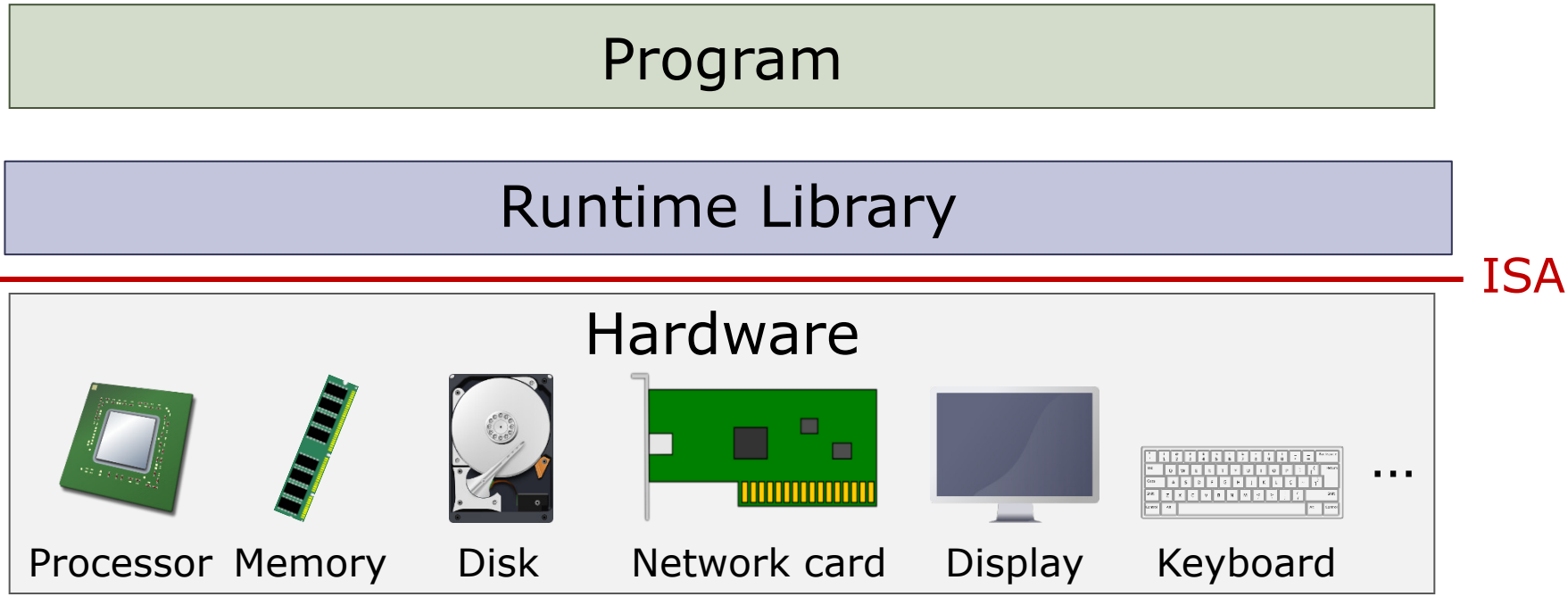
Single-Program Machine (with RTL)



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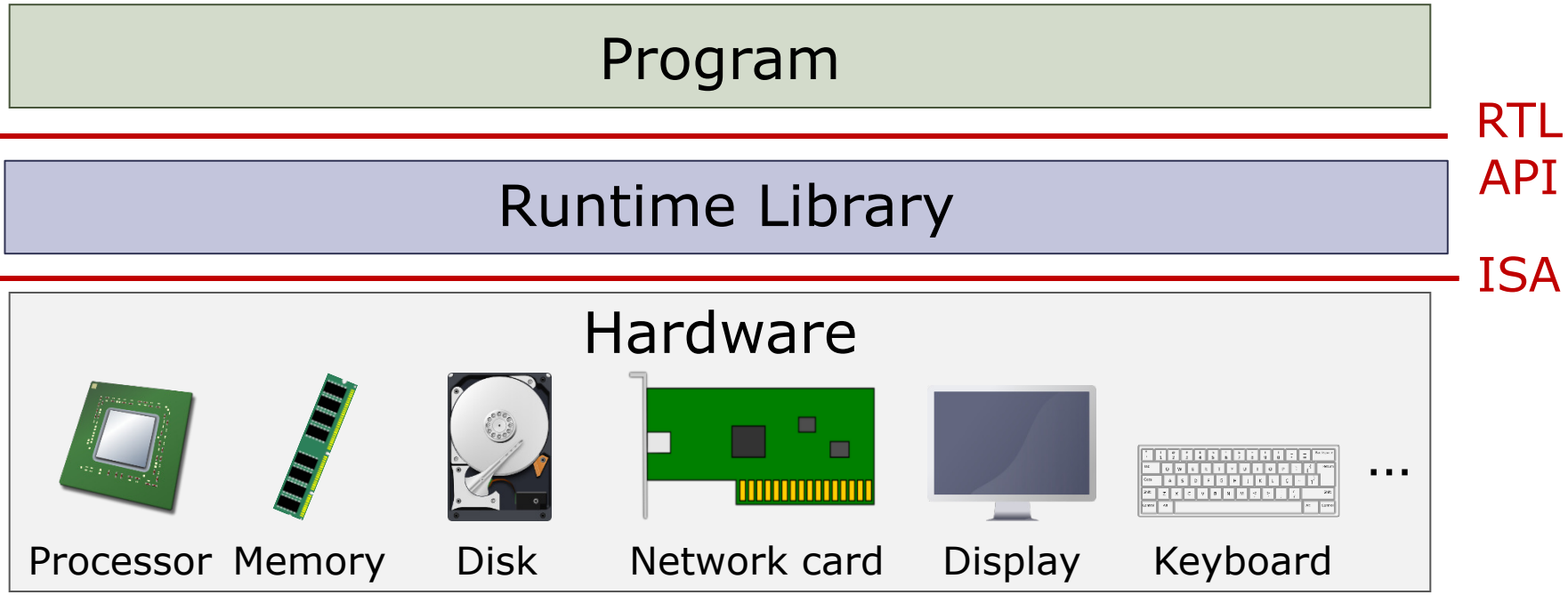

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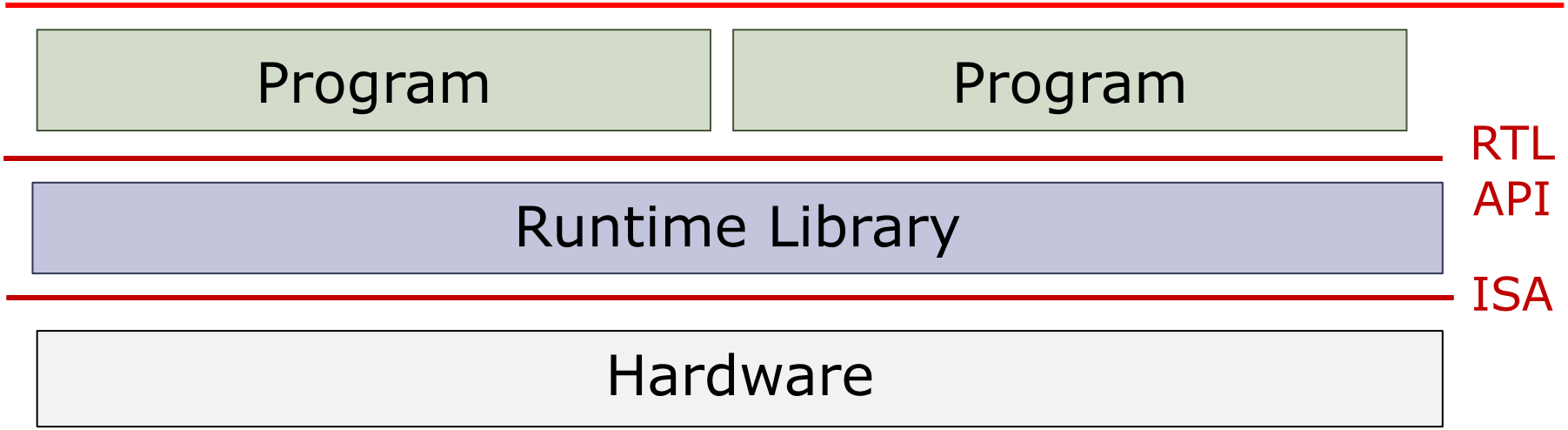
Multi-Program Machine (1st attempt)



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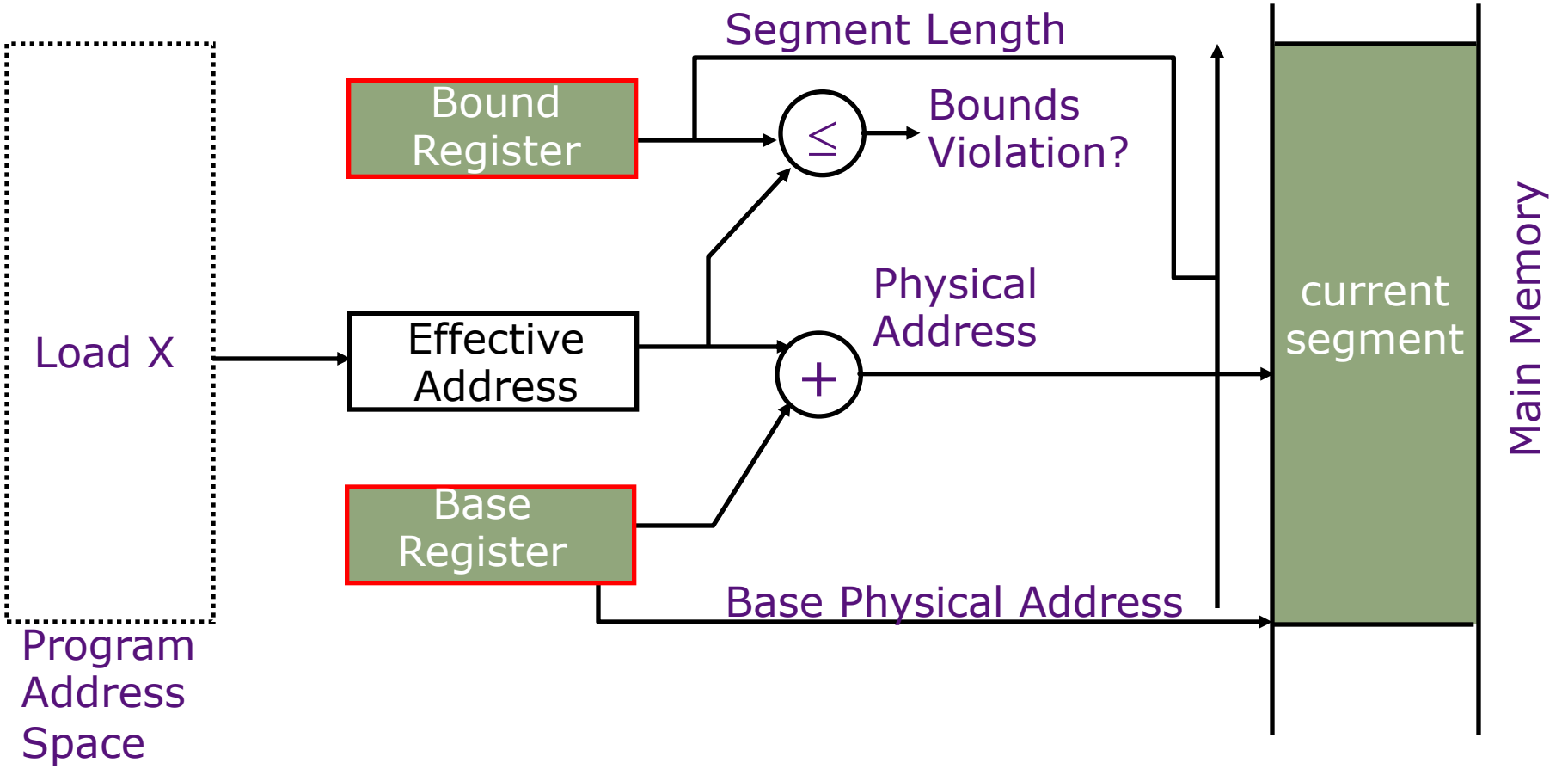
Any problems?

Simple Base and Bound Translation



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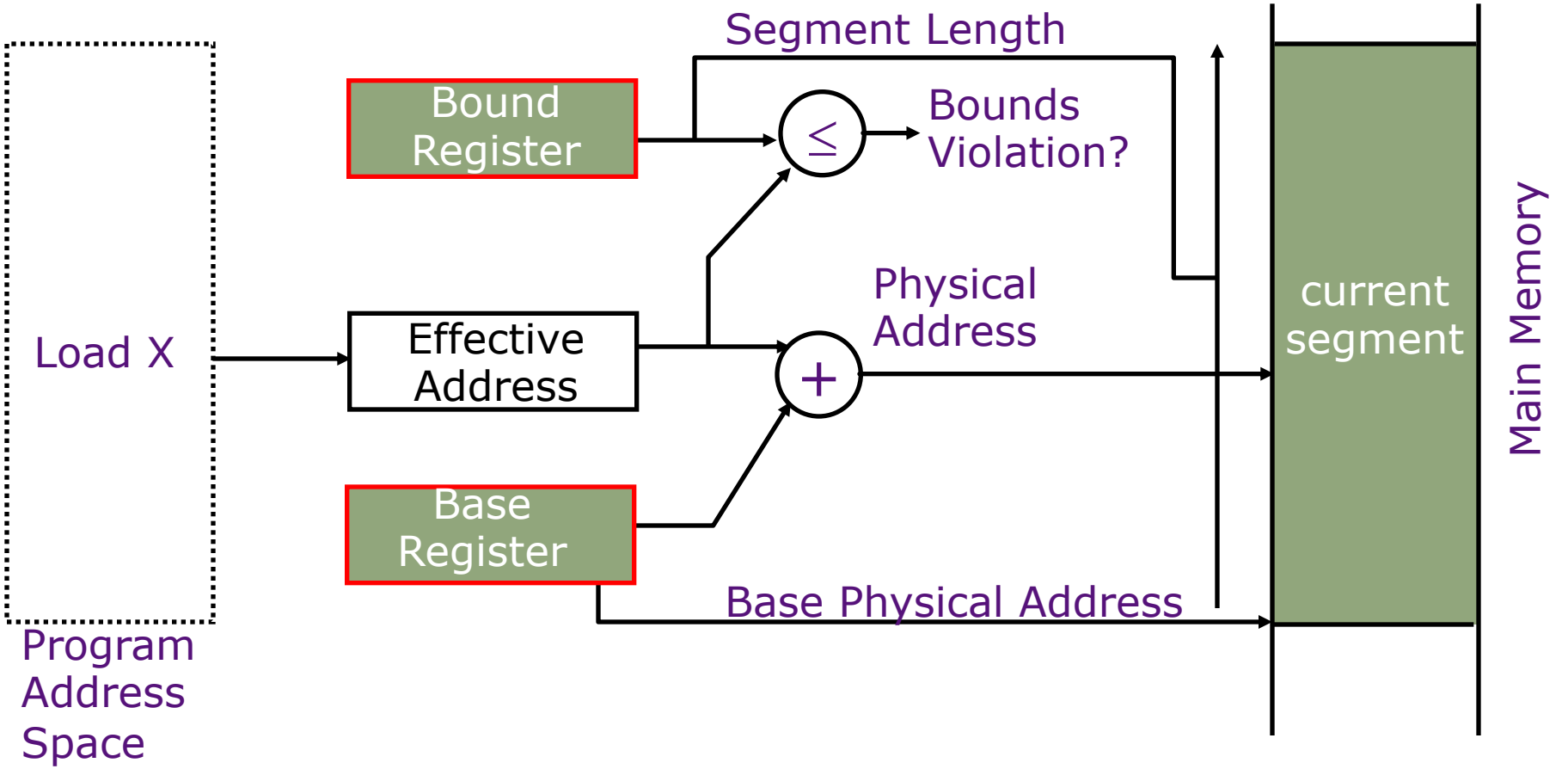

Introduce a new privileged mode in which the base and bounds registers are visible/accessible.

Protecting Memory

Page Table Entry

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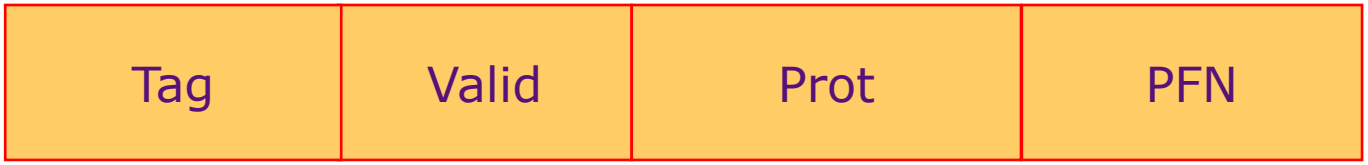
TLB Entry



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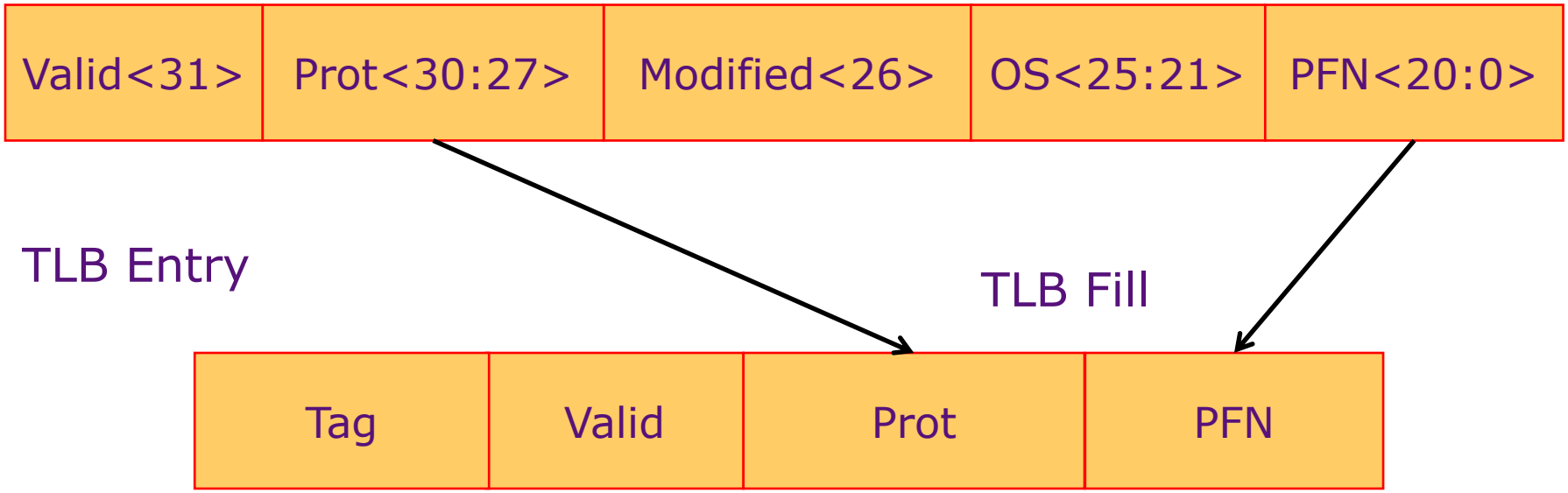

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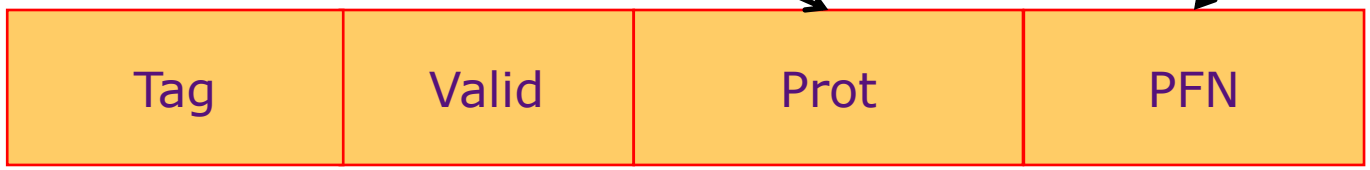
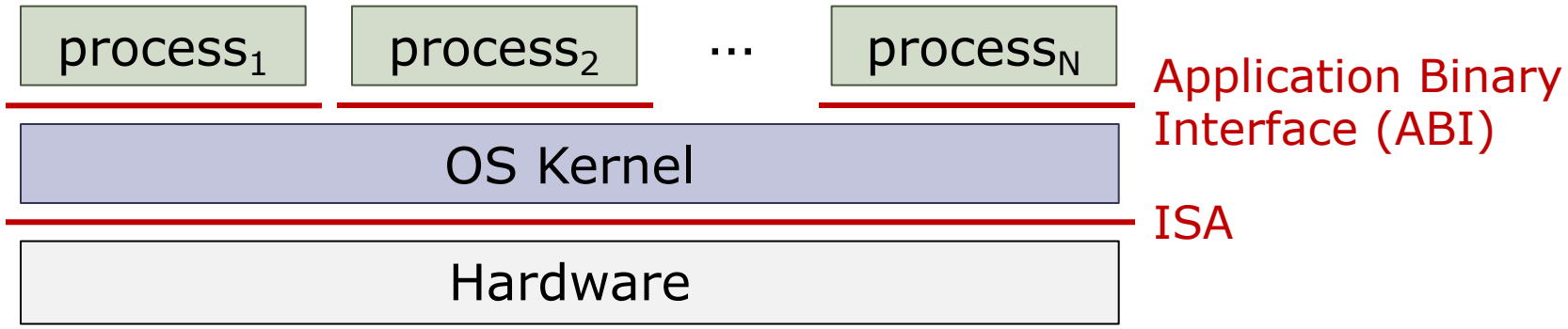
TLB Fill



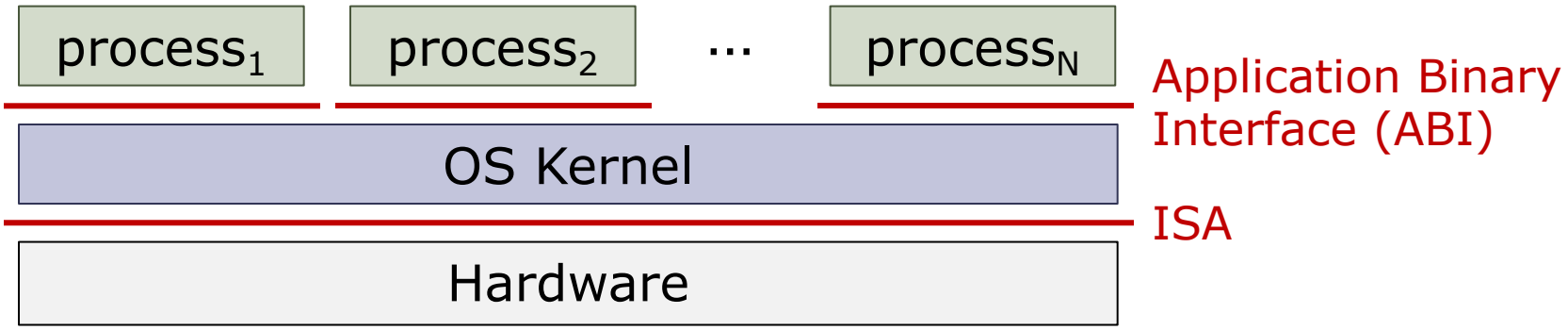
- TLB fill is a privileged operation.
- TLB access checks if protection allows access for current mode

Operating Systems



- Operating System (OS) goals:

Operating Systems



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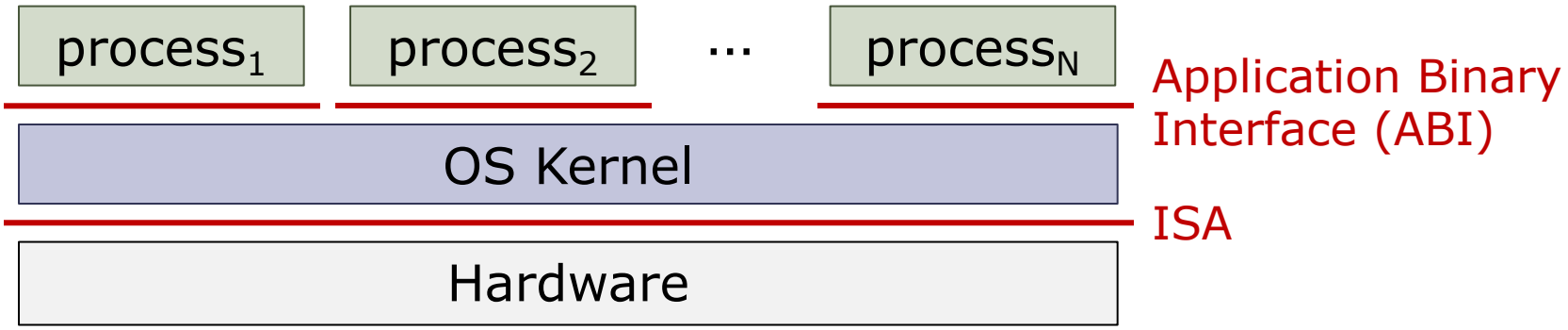

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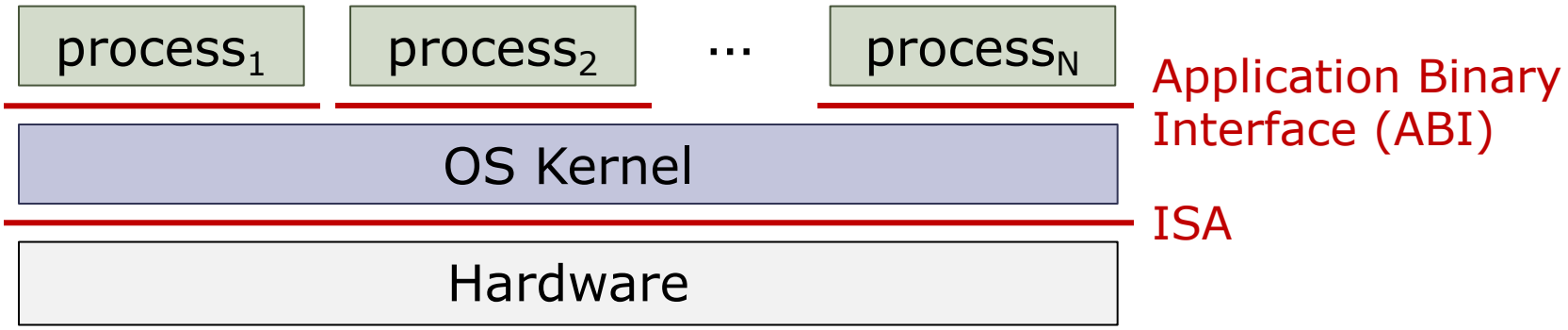

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  - Protection and privacy: Processes cannot access each other's data

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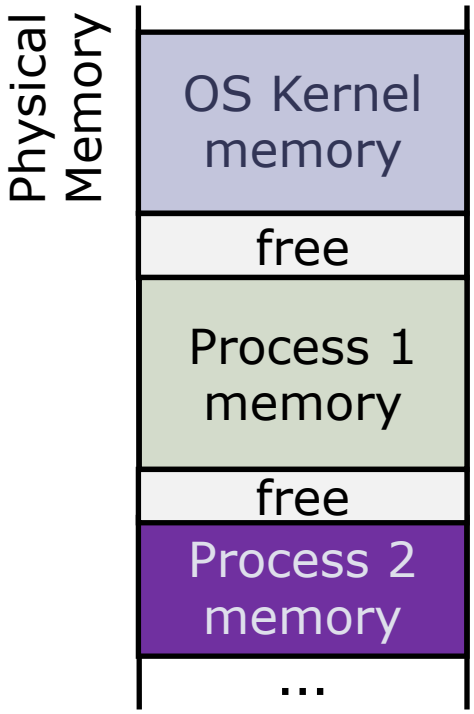

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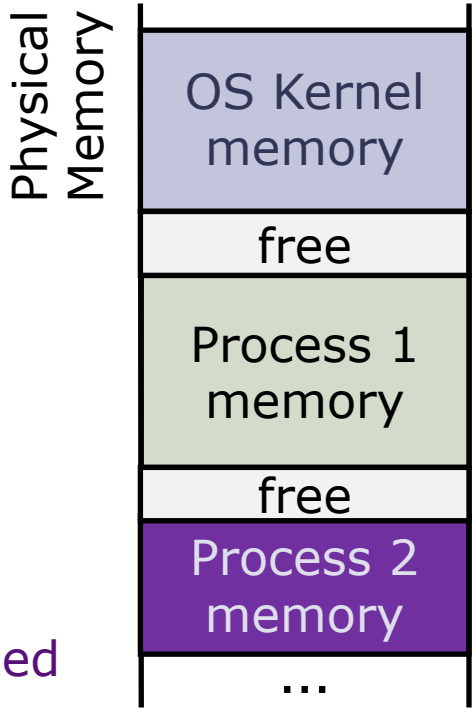

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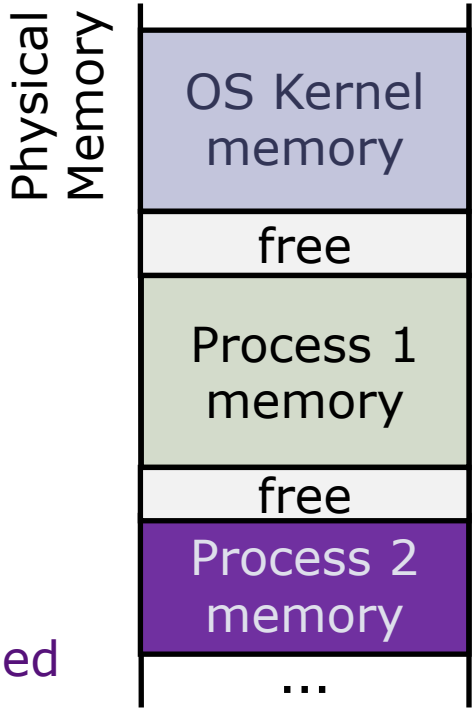

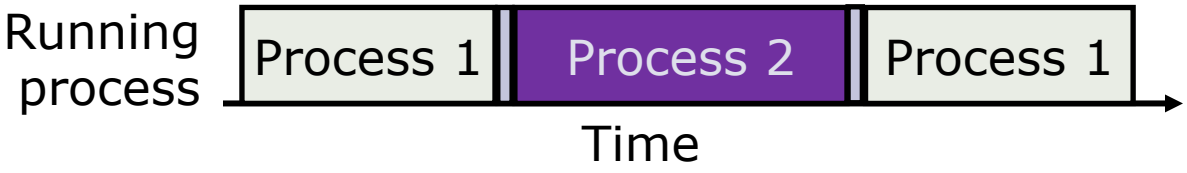

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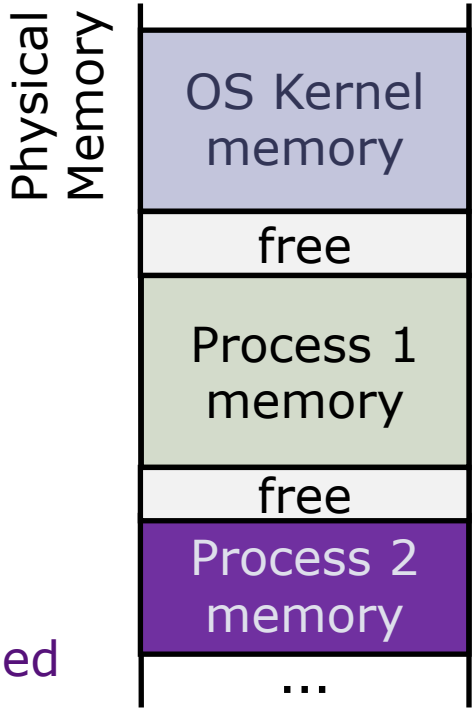

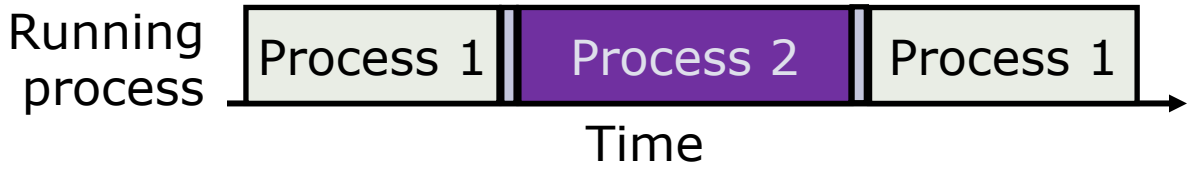

- The OS kernel lets processes invoke system services (e.g., access files or network sockets) via system calls

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- Privileged instructions and registers that are only available in supervisor mode
- Traps (exceptions) to safely transition from user to supervisor mode

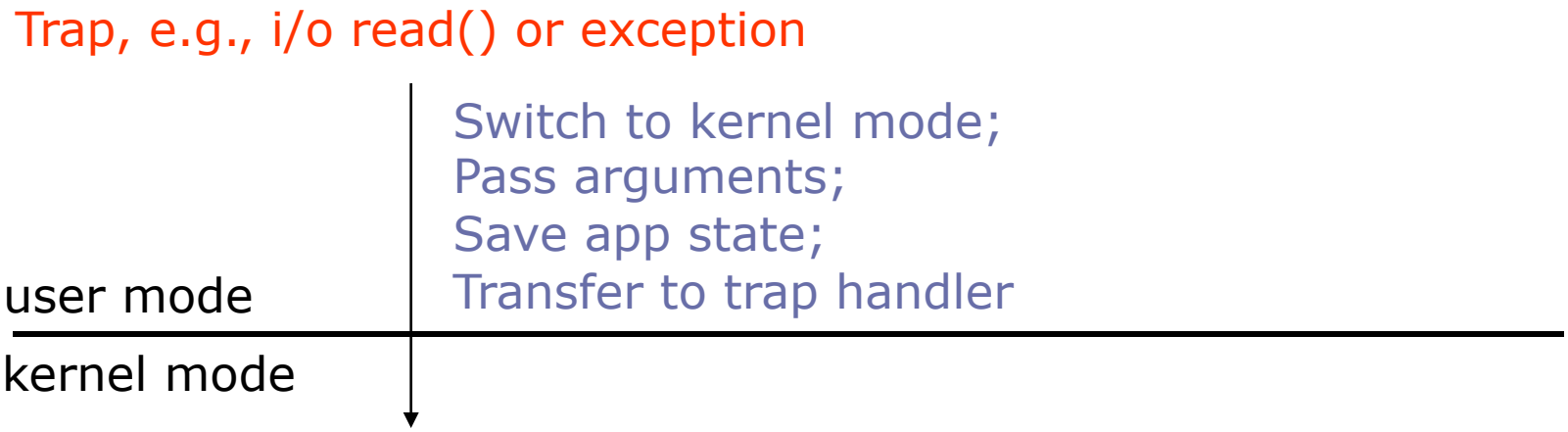
Process Mode Switching

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

user mode

kernel mode

Process Mode Switching



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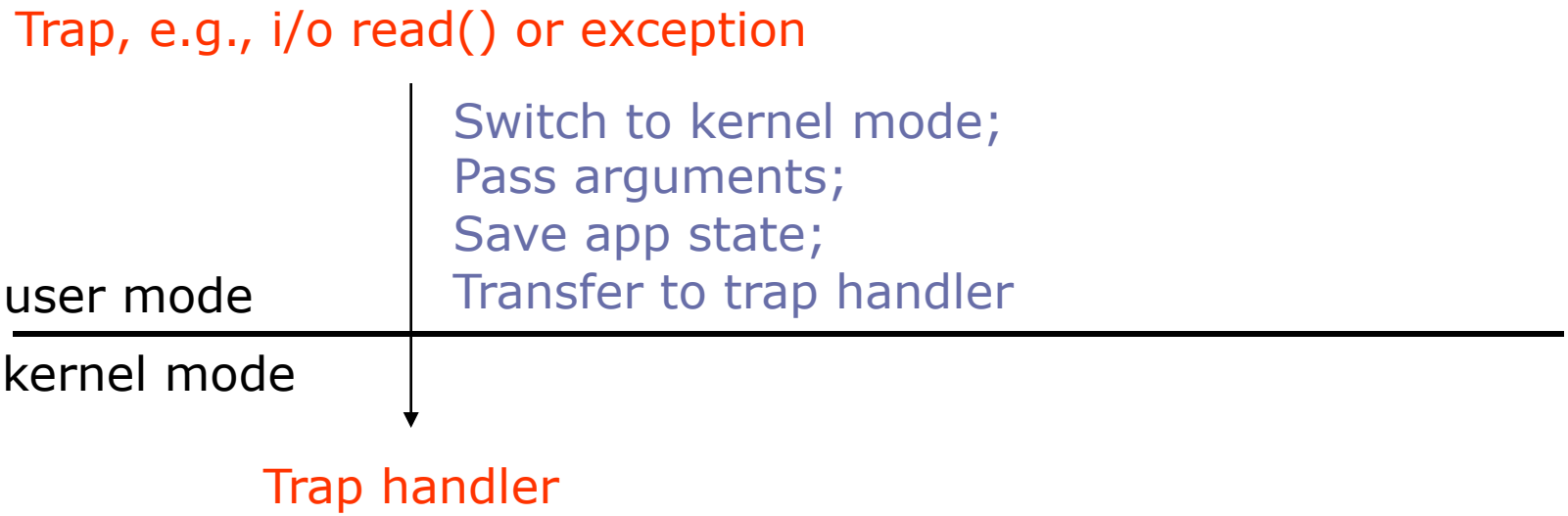

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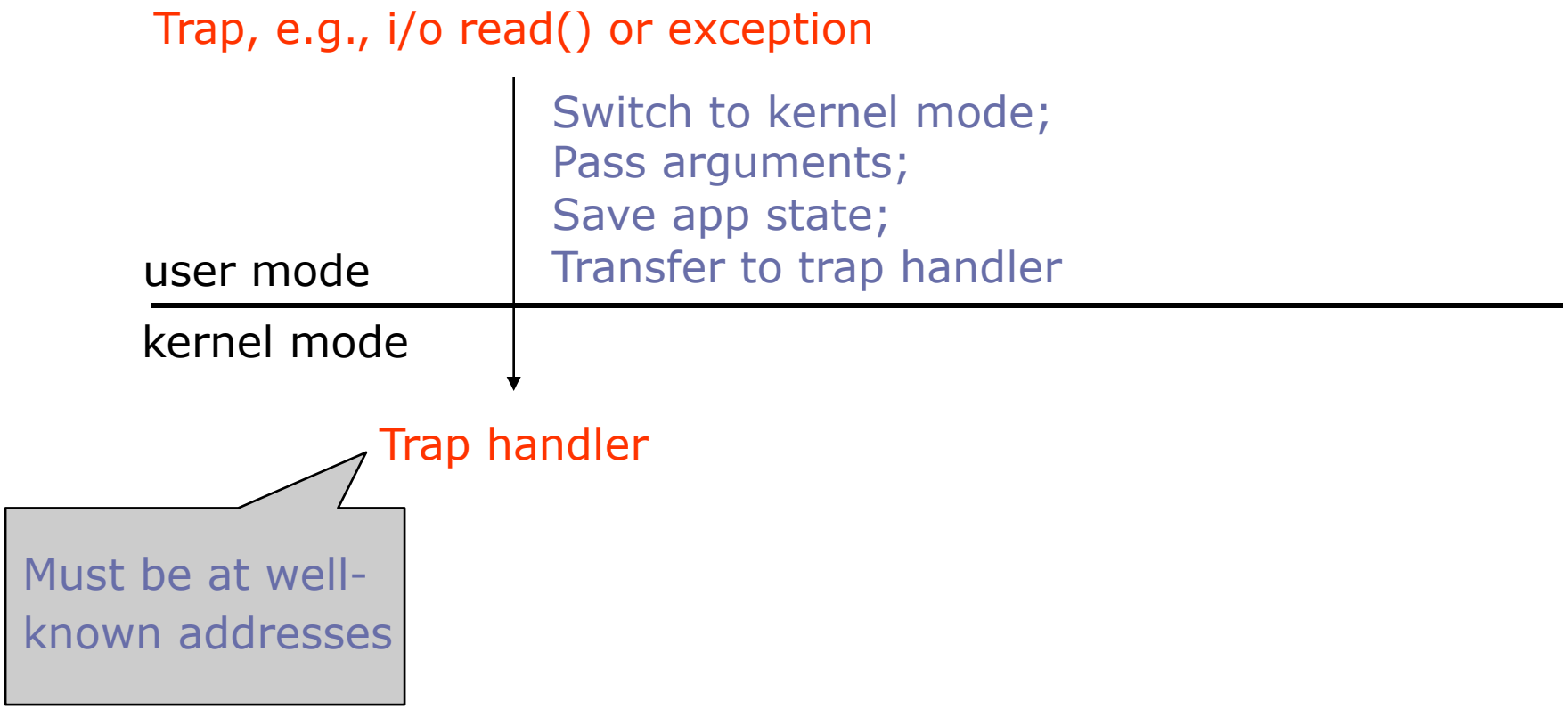

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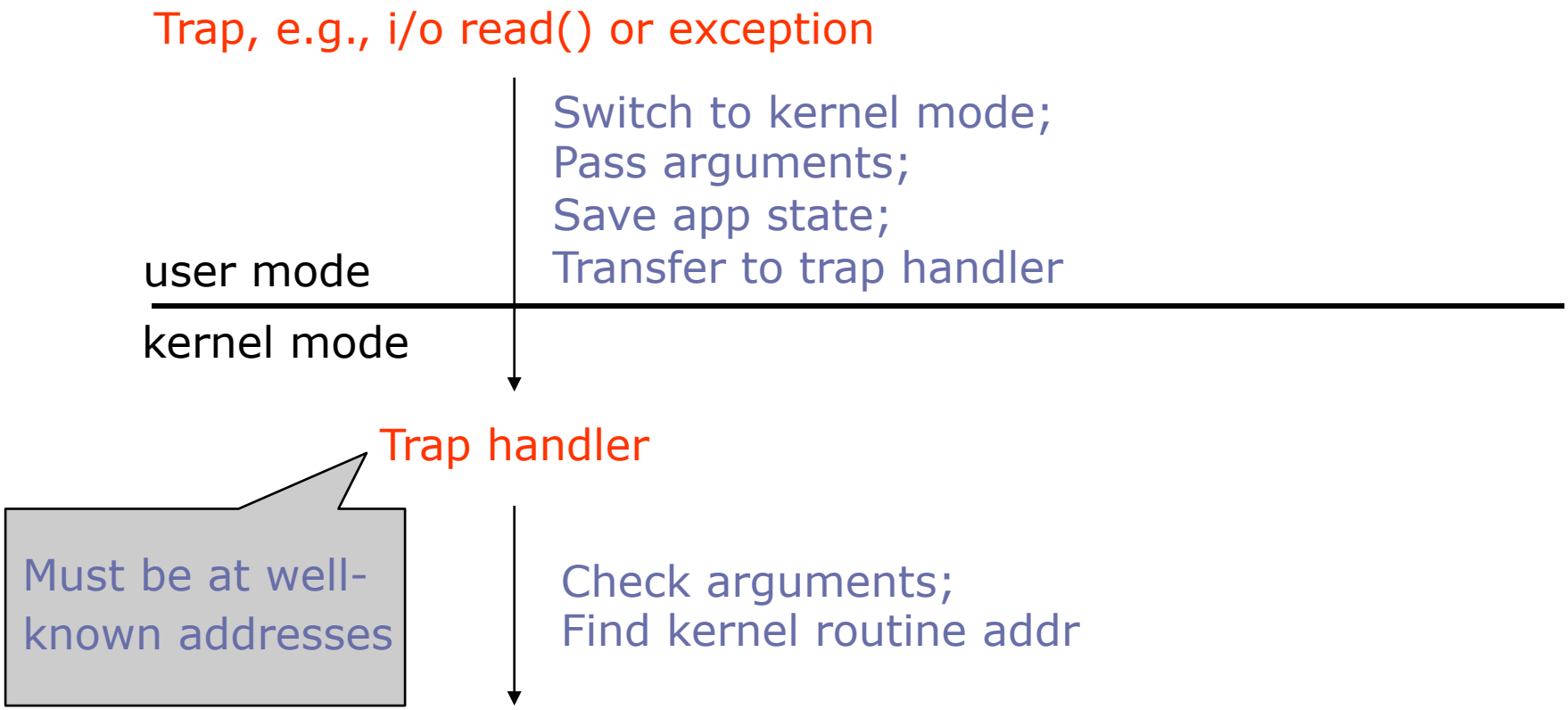

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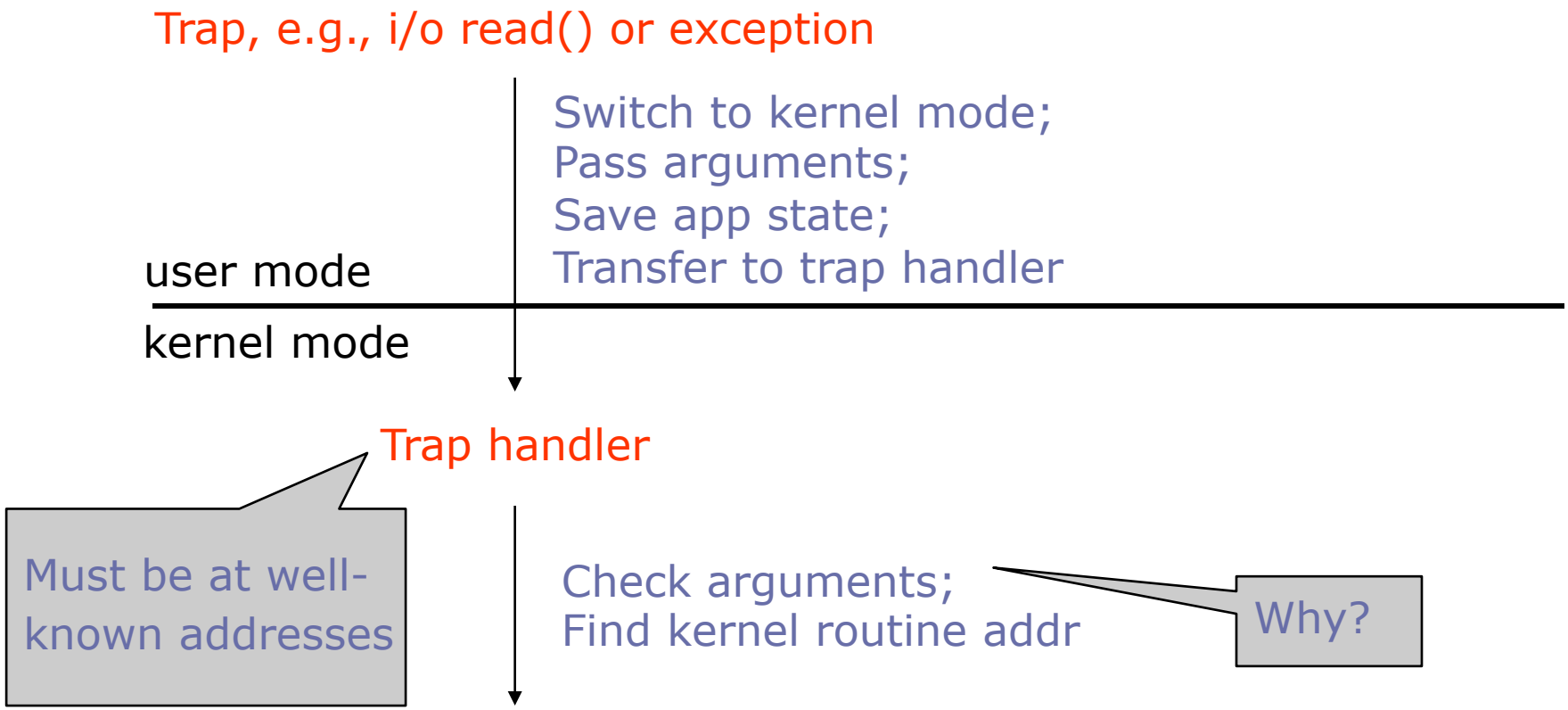

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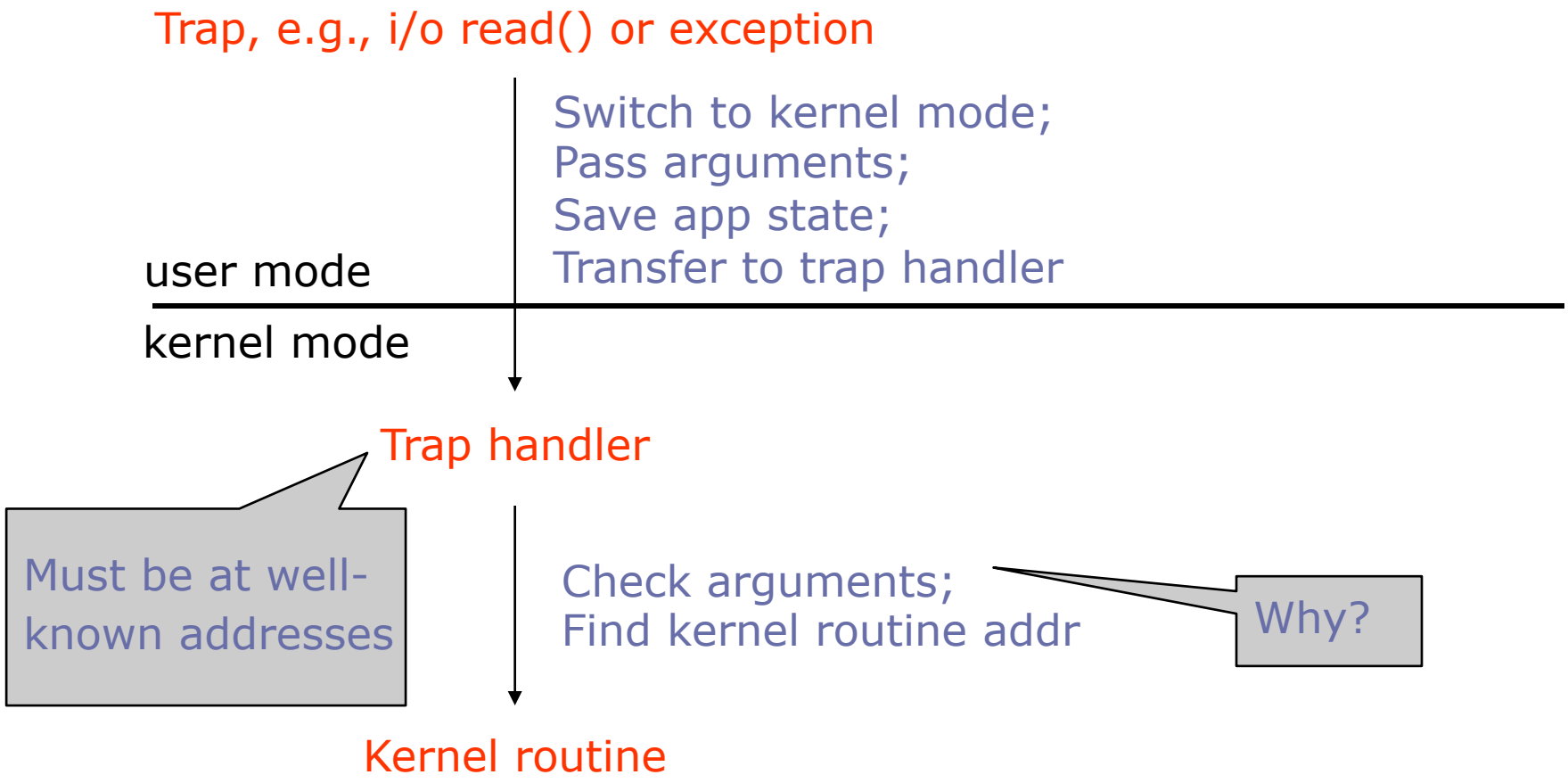

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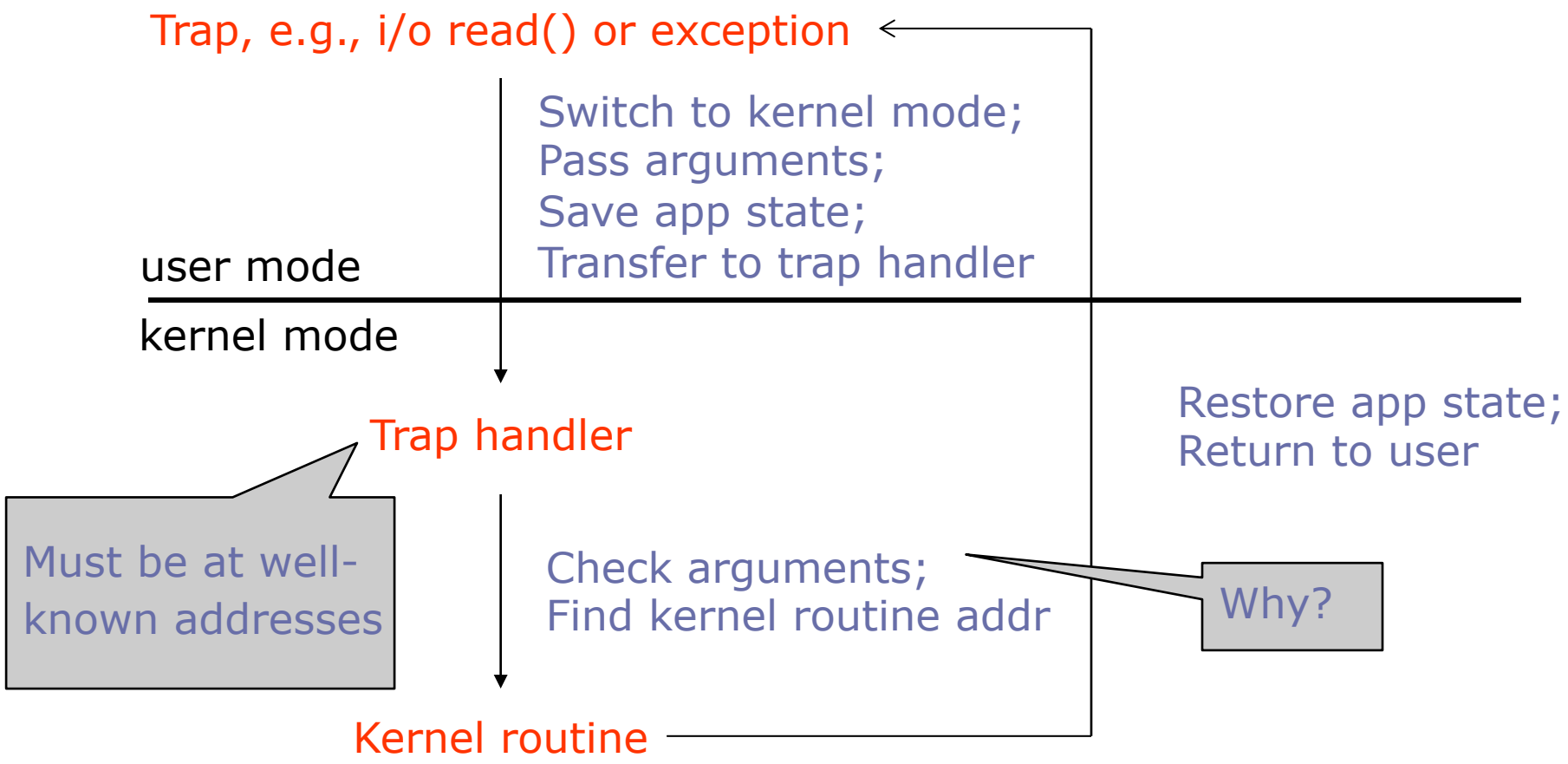
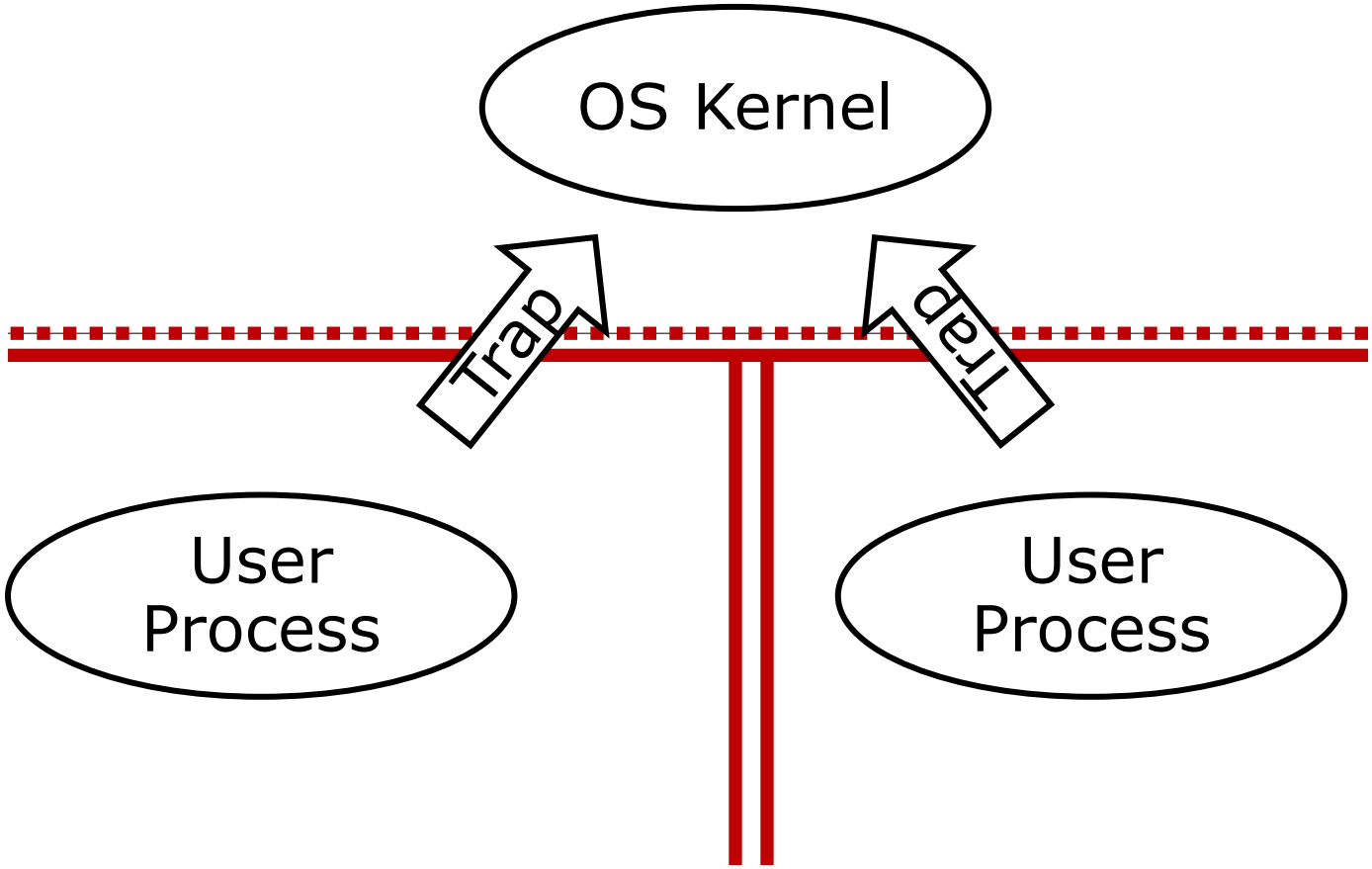


Protection – Single OS



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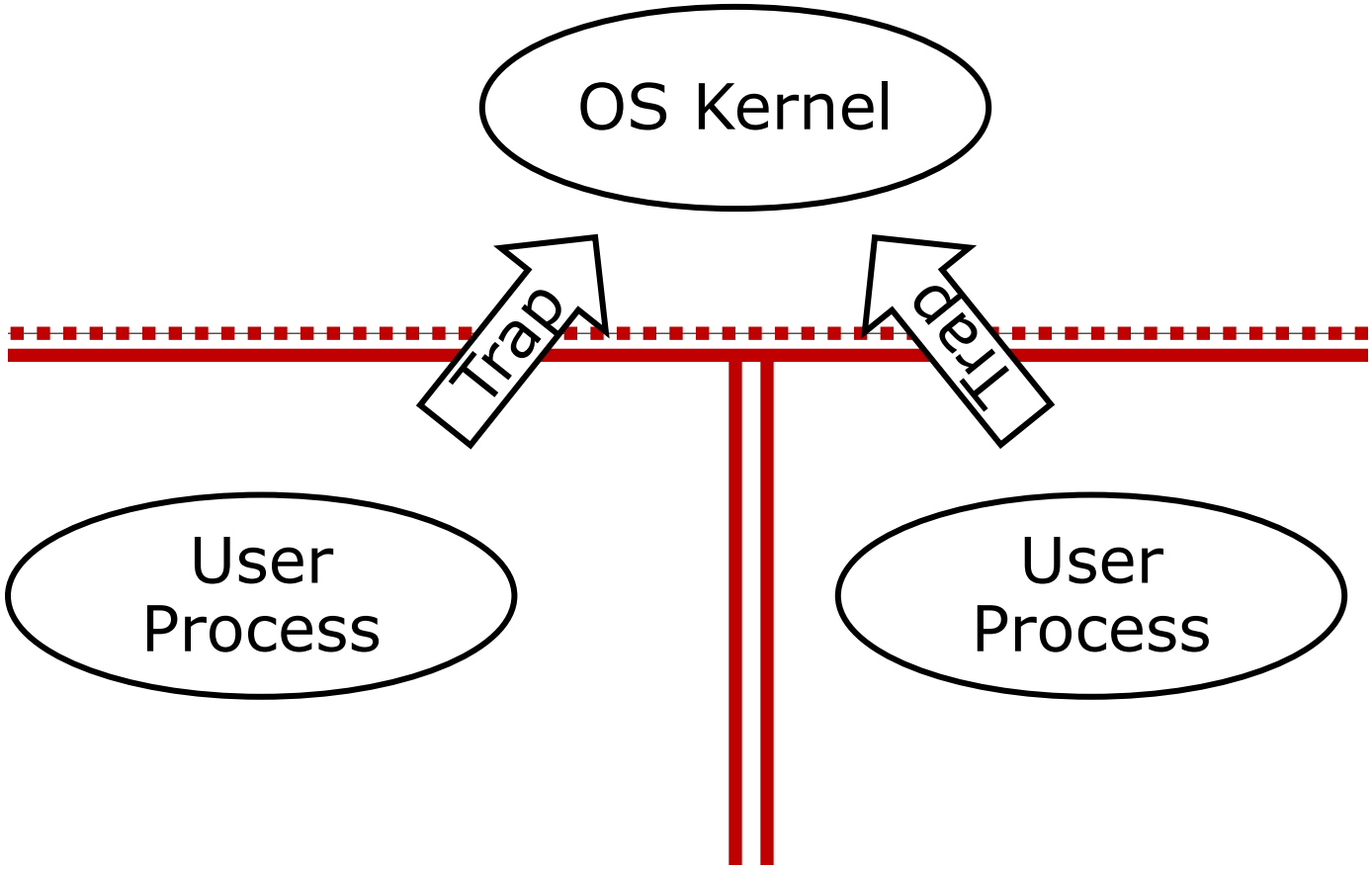

Key idea: Provides a strong abstraction that cannot be escaped

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  - …but this machine does not exist in physical hardware

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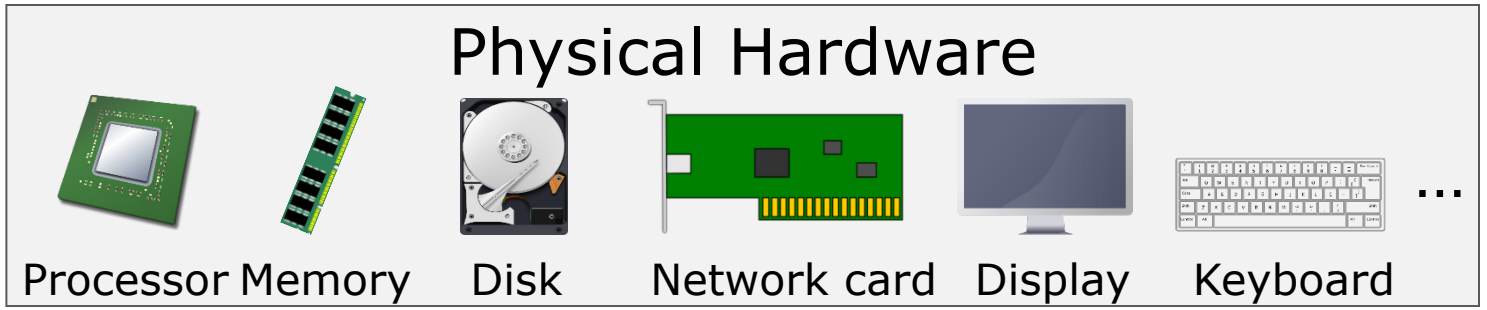

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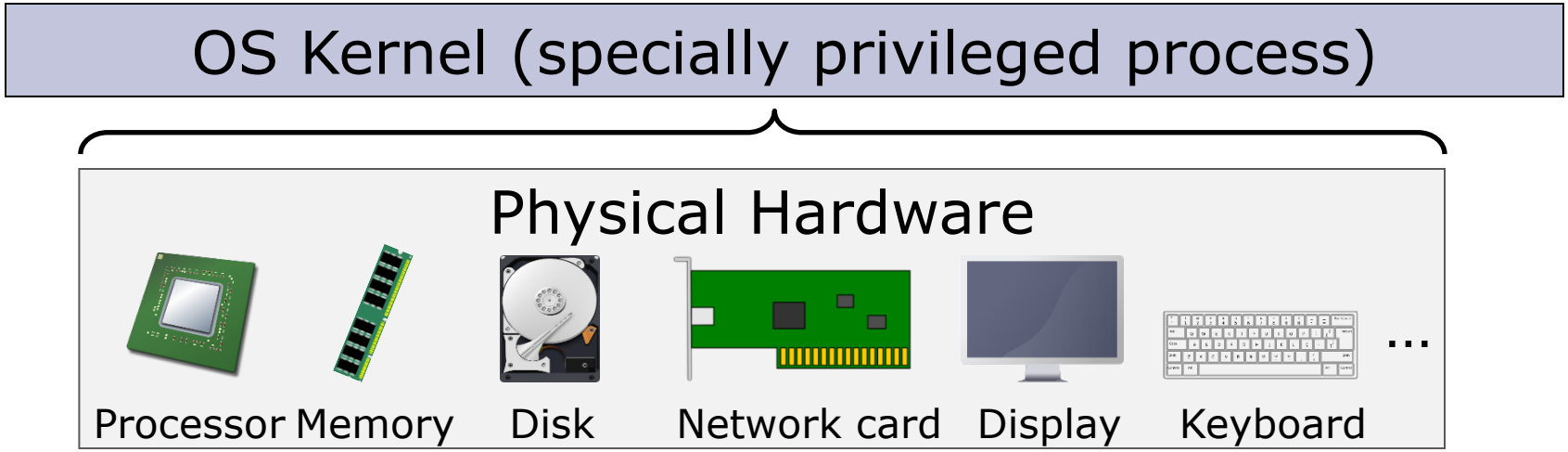

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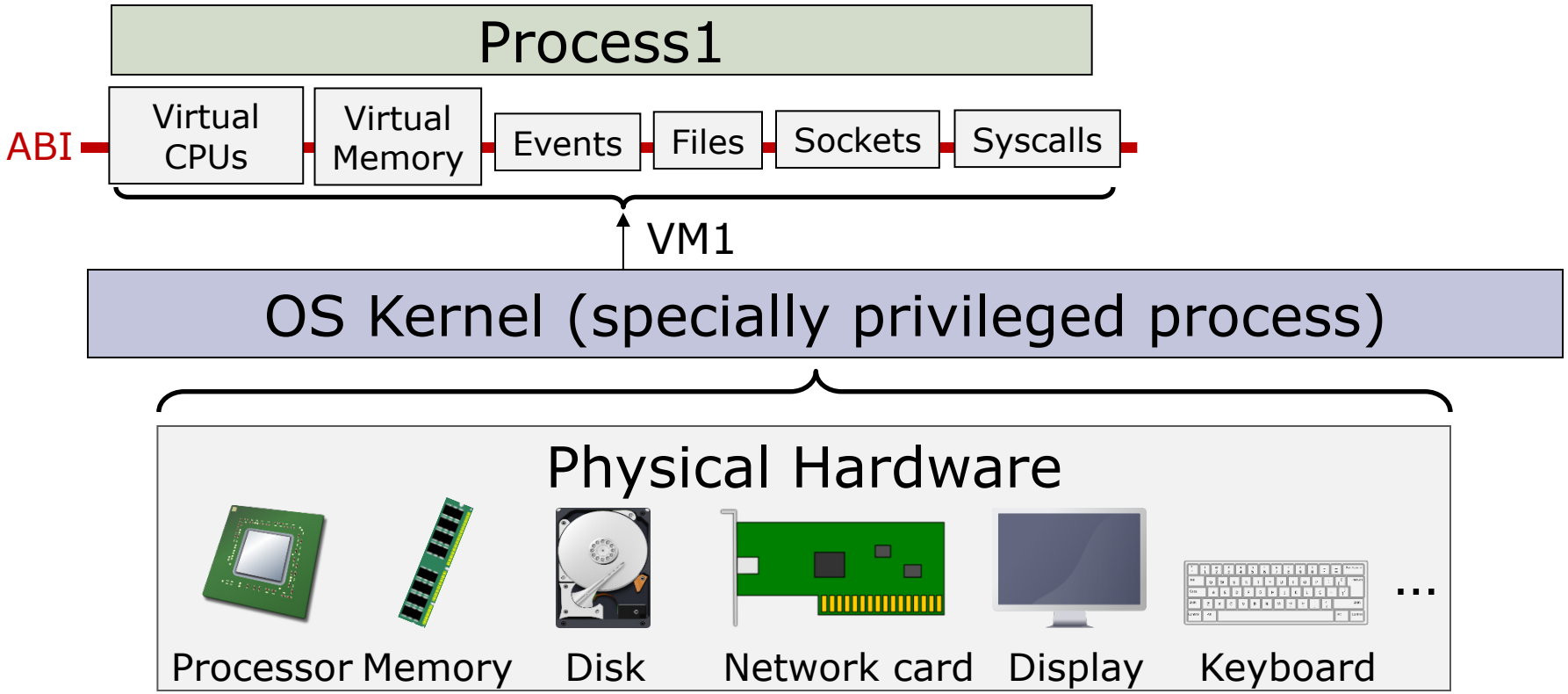

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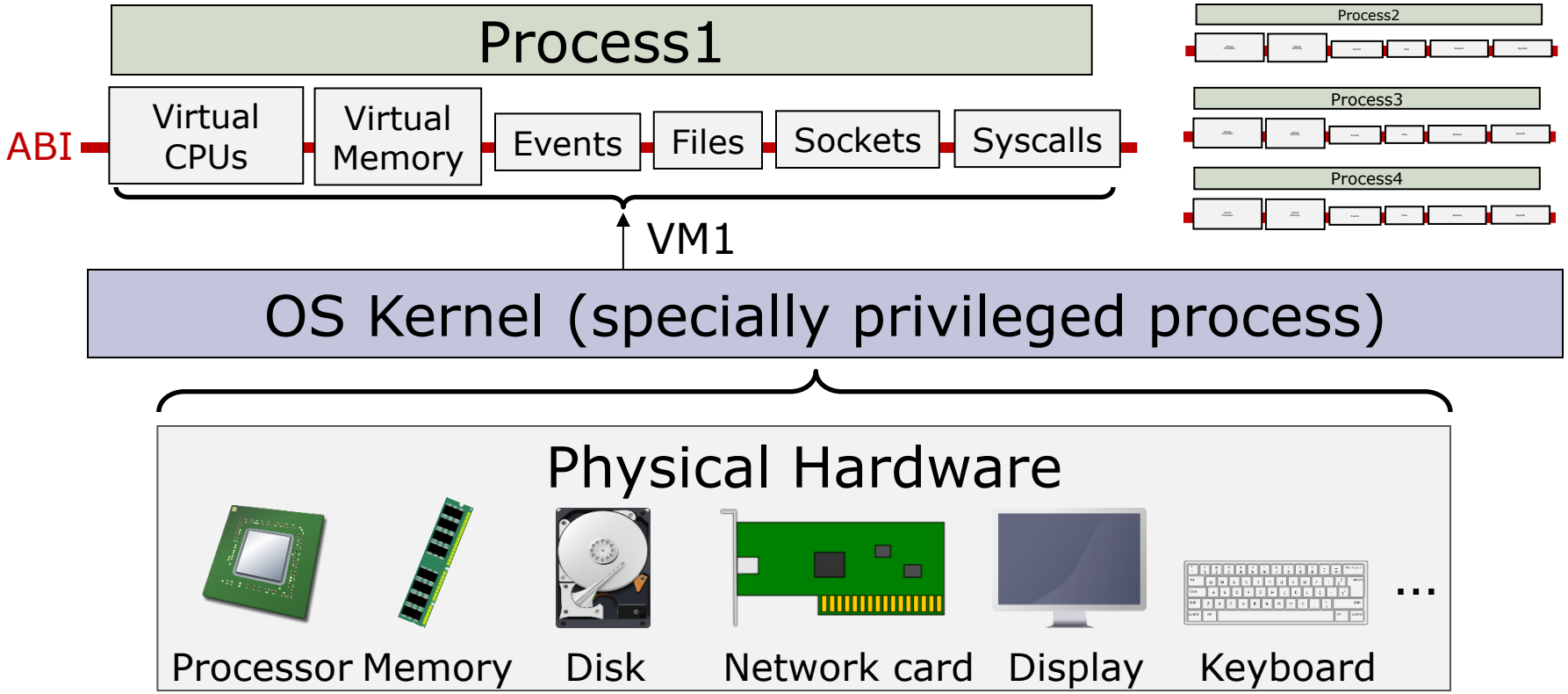
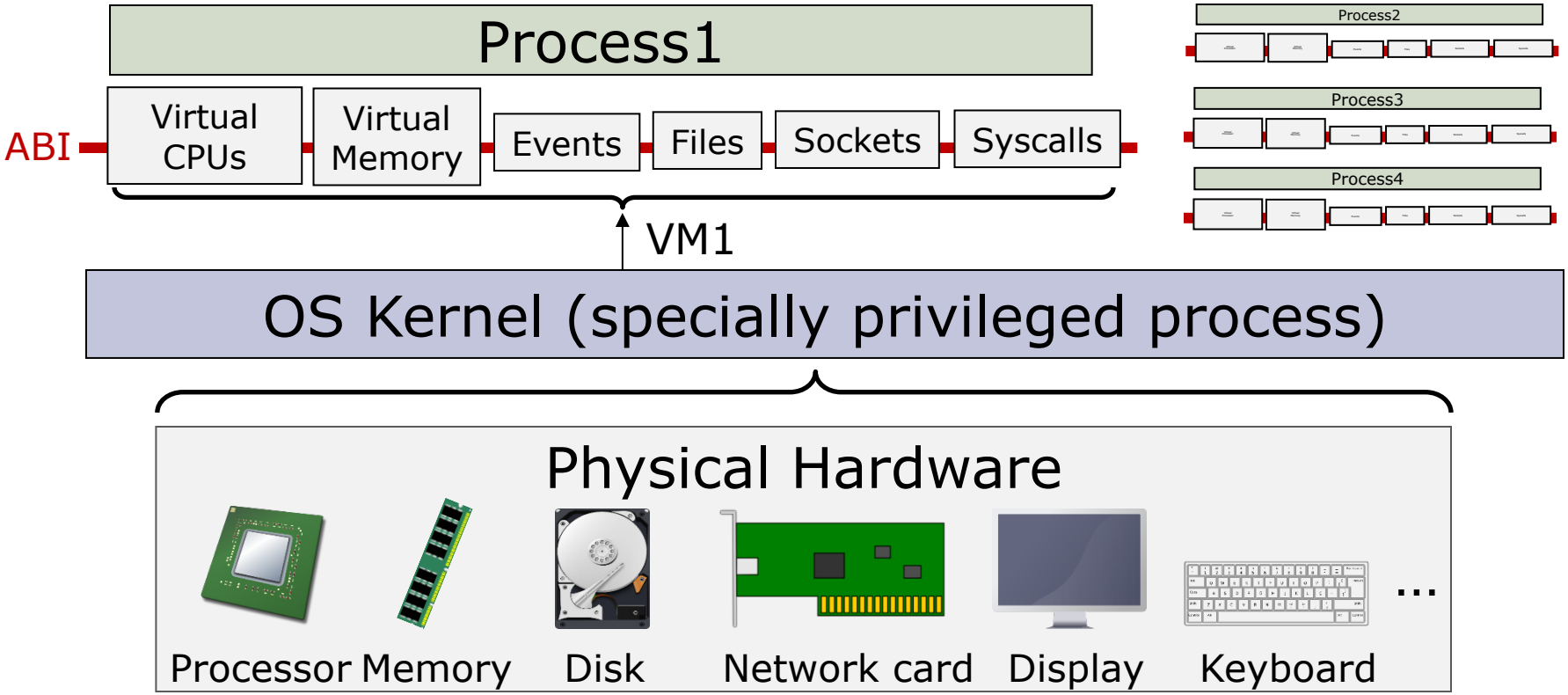


Virtual Machines

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



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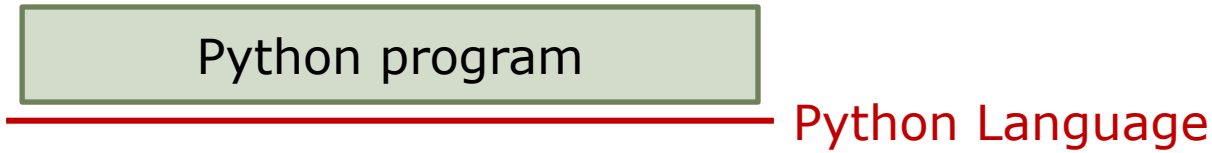

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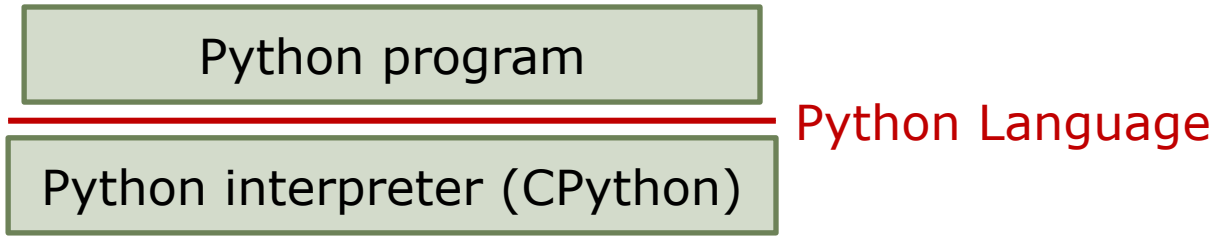

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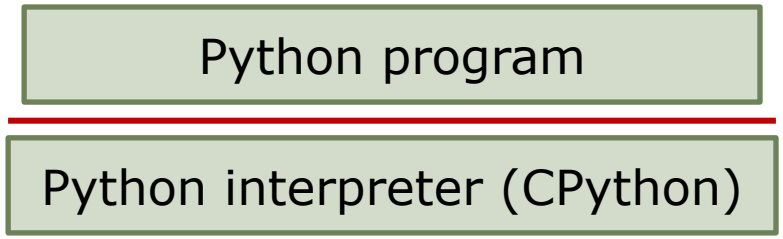

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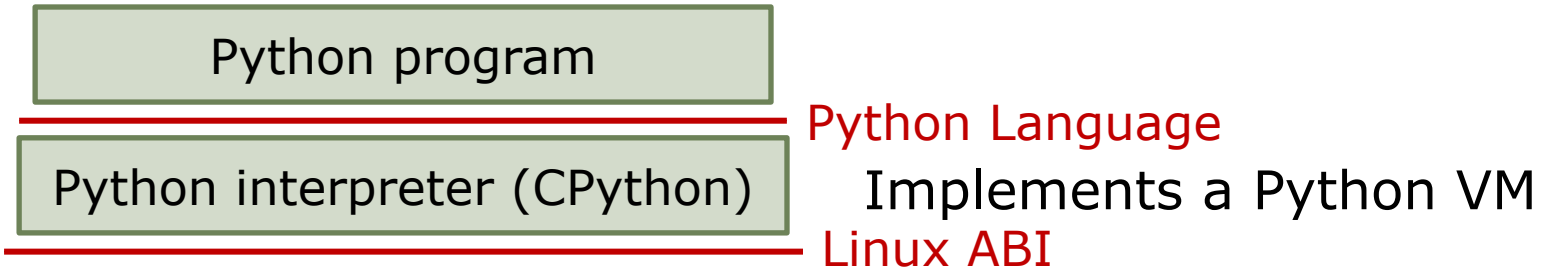

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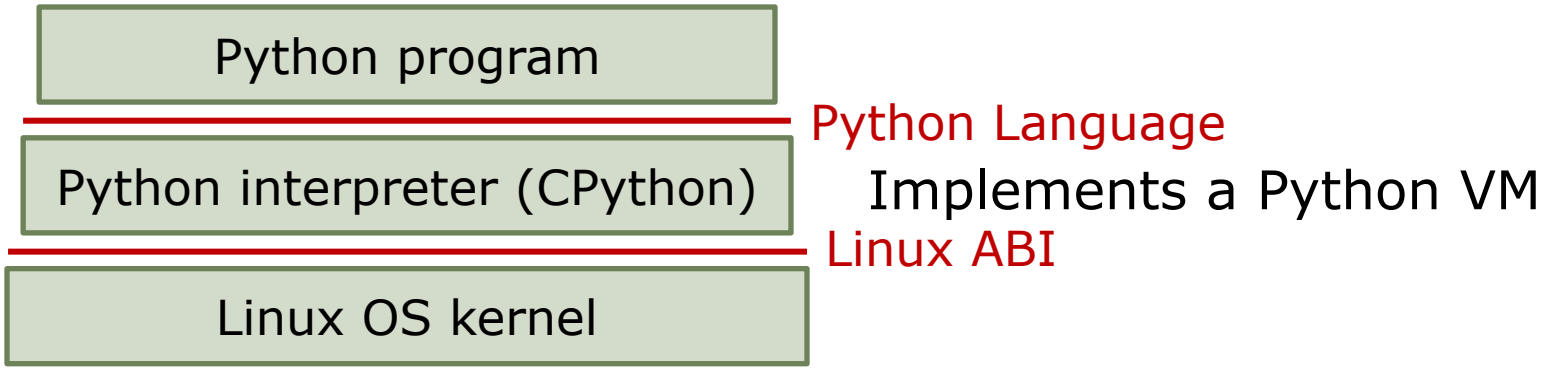

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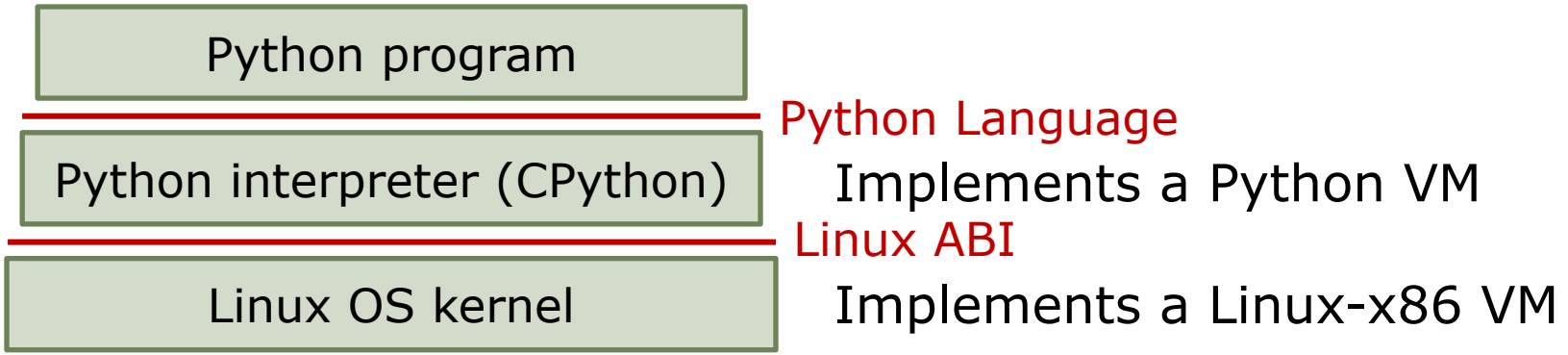

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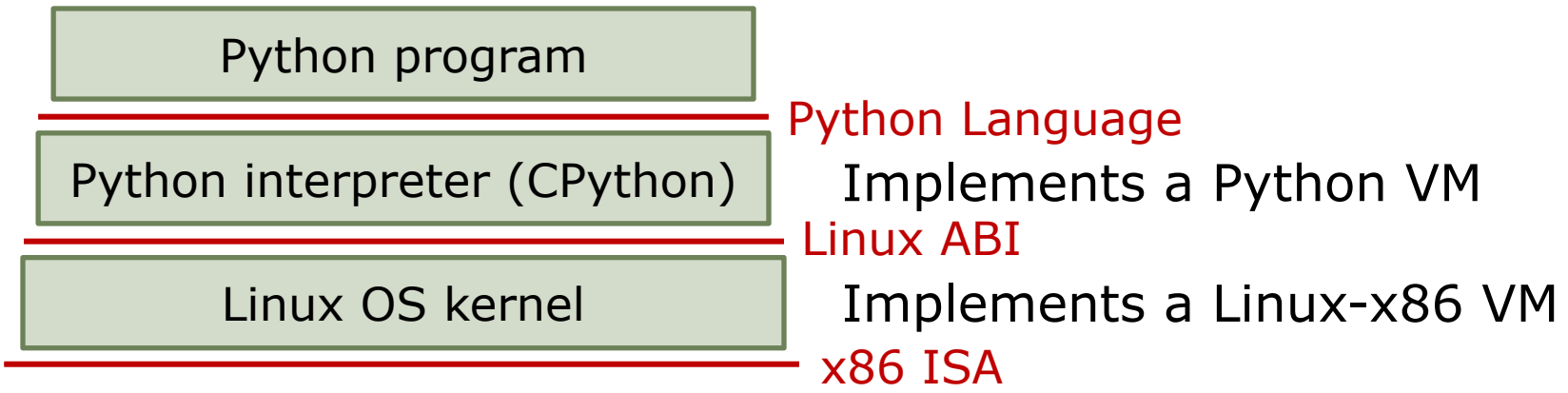

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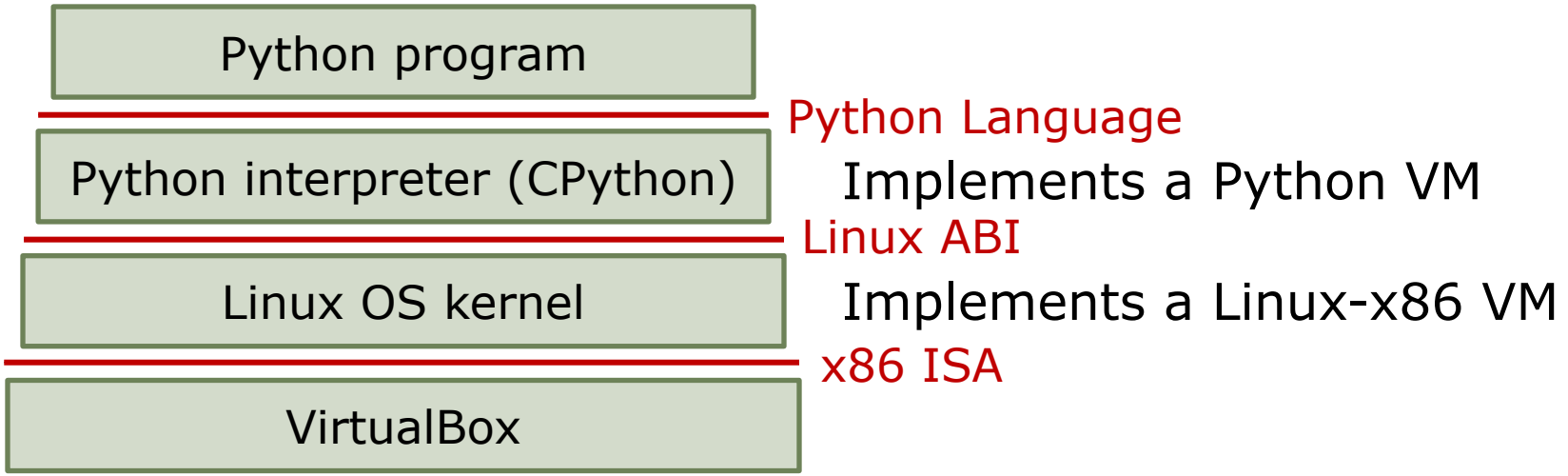

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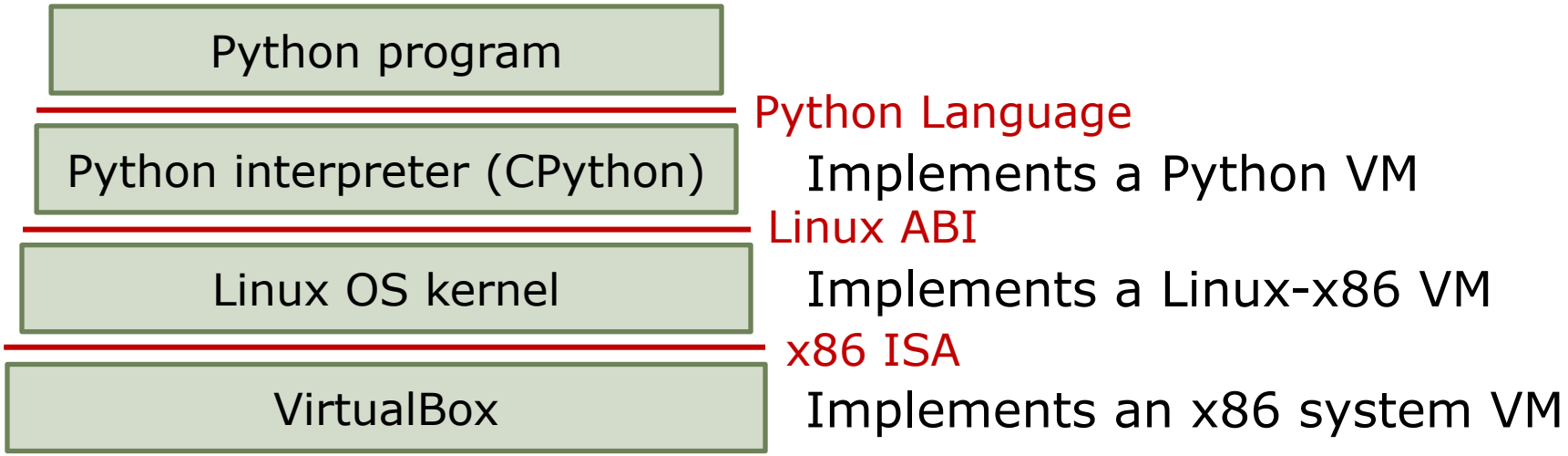

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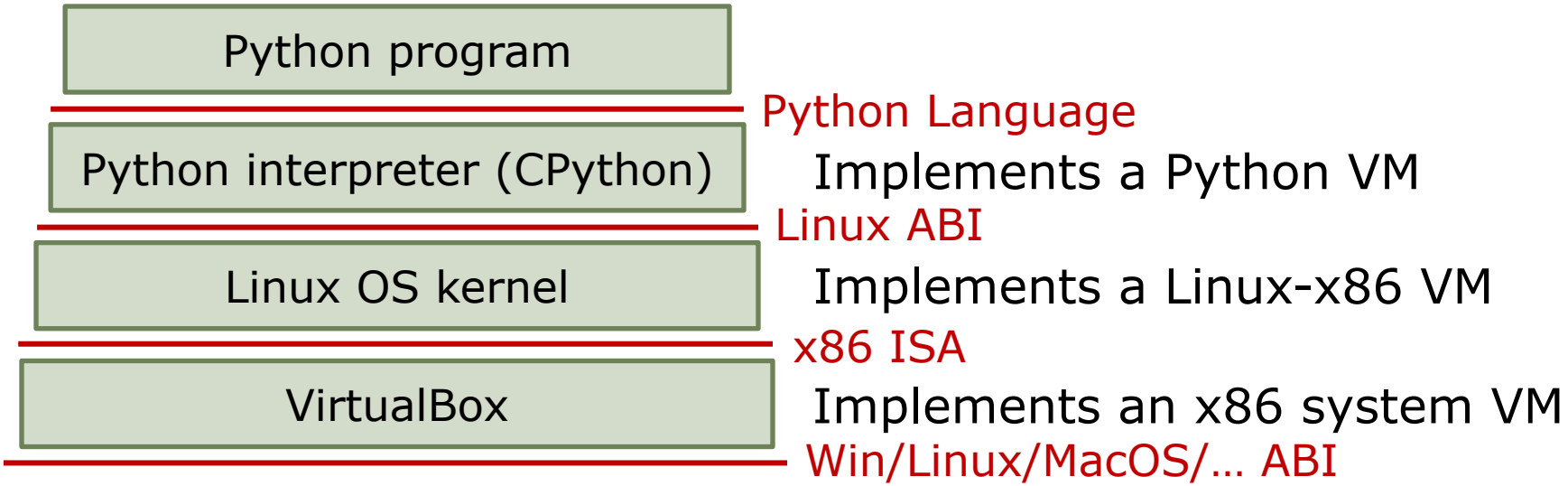

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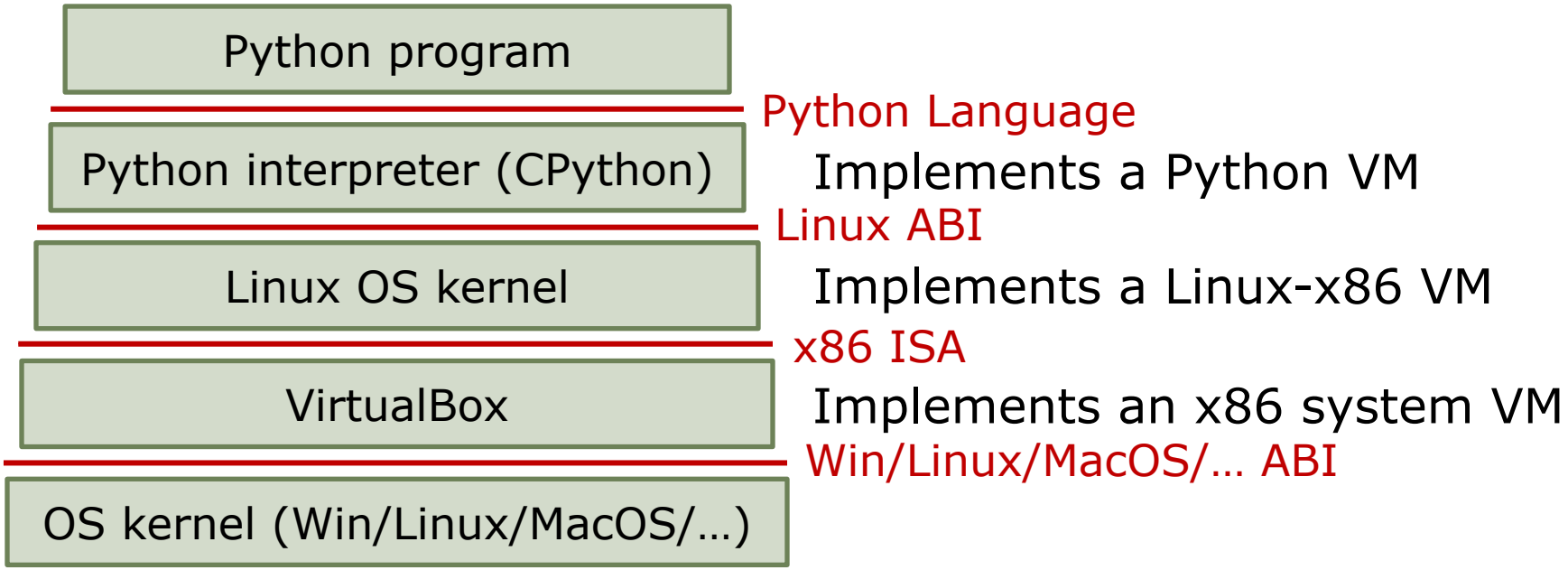

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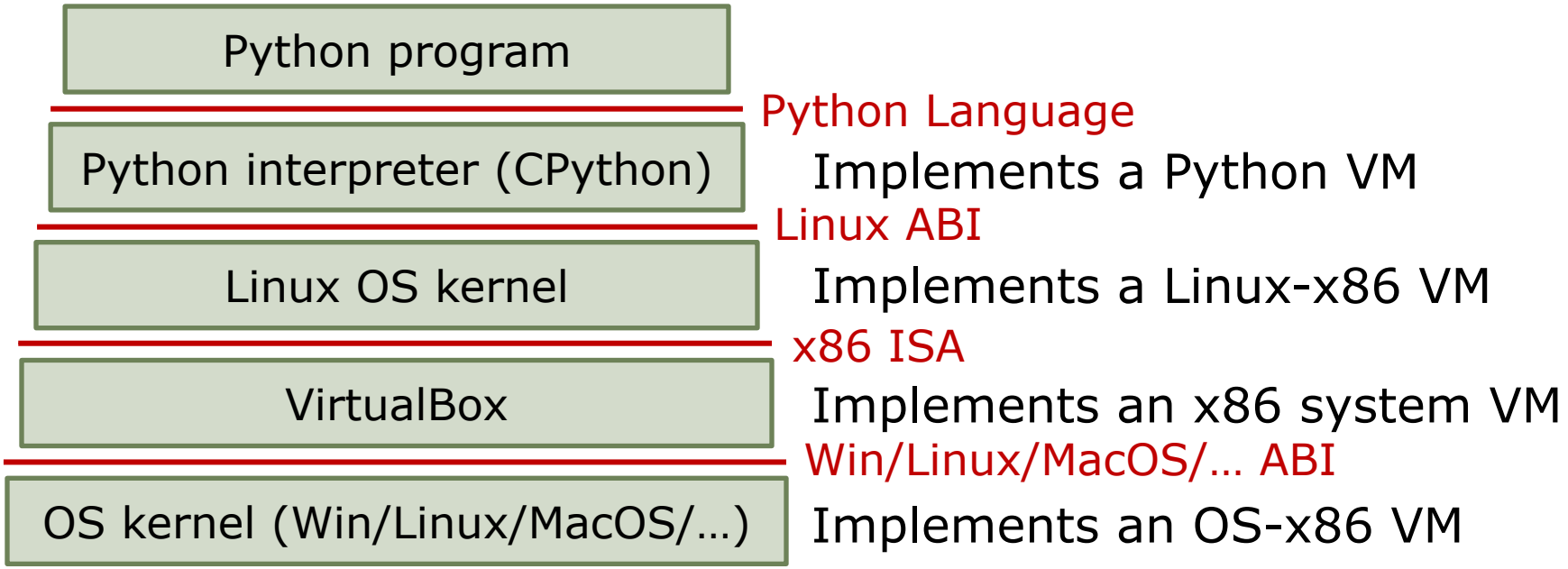

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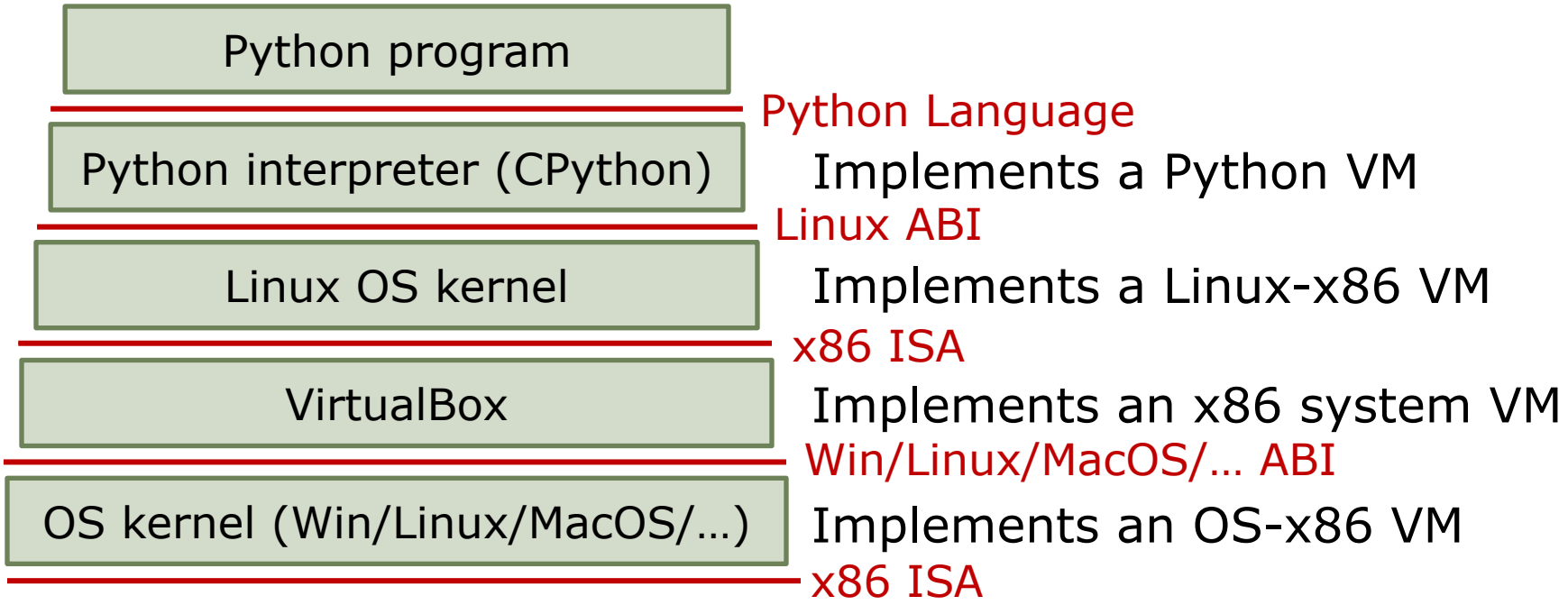

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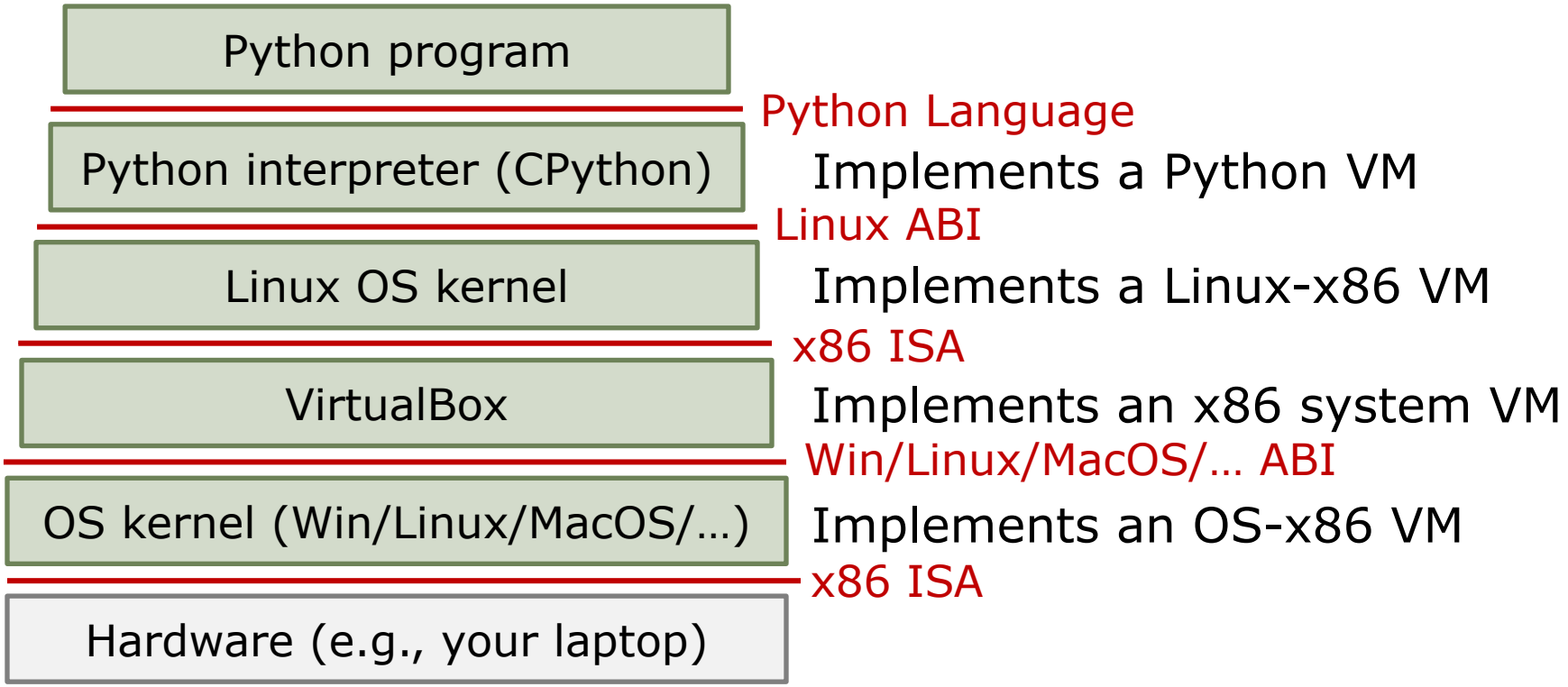

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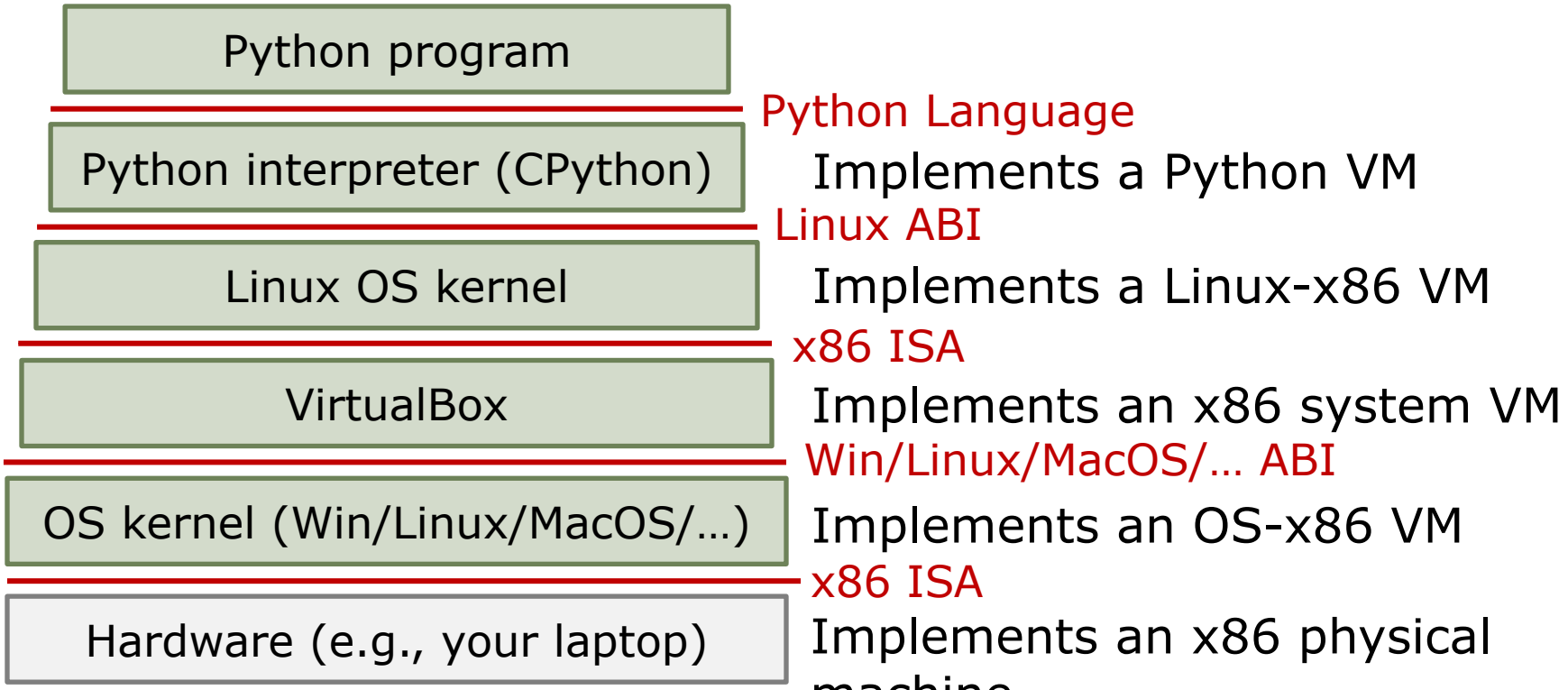

Application-level virtualization

- 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 programs for one ISA on hardware with different ISA

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  - Sun's HotSpot Java JIT (just-in-time) compiler
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- Infrequent but difficult operand values can cause trap
  - 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

Implementing Virtual Machines

- Virtual machines can be implemented entirely in software, but at a performance cost
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- We want to support virtual machines with minimal overheads → need hardware support!

Motivation for Multiple OSs

Some motivations for using multiple operating systems on a single computer:

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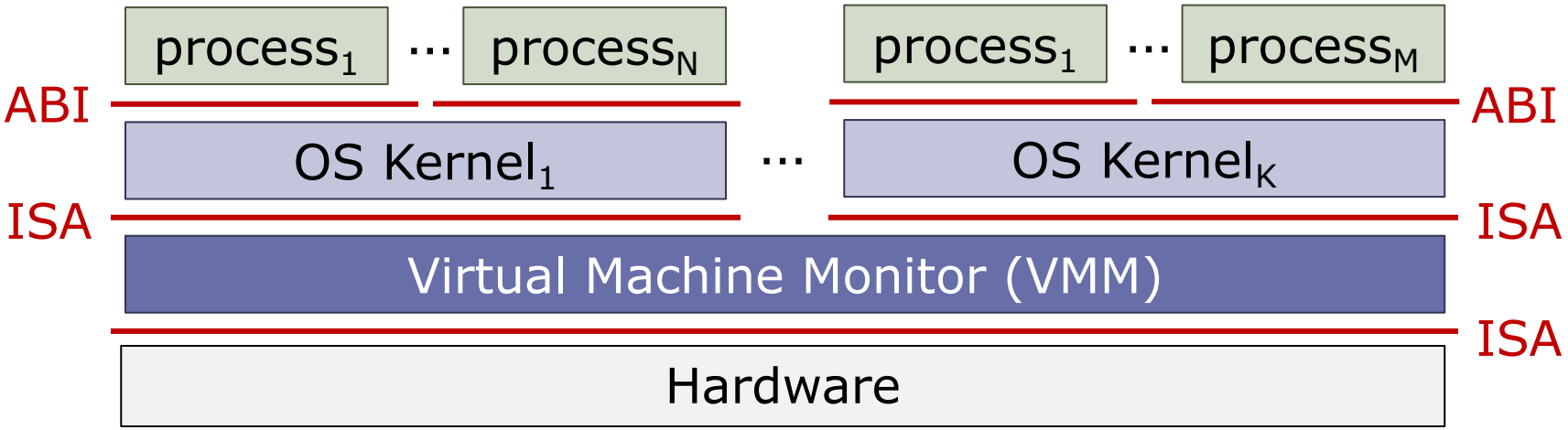
- Allows for load balancing and migration across multiple machines
- Allows operating system development without making entire machine unstable or unusable

Supporting Multiple OSs



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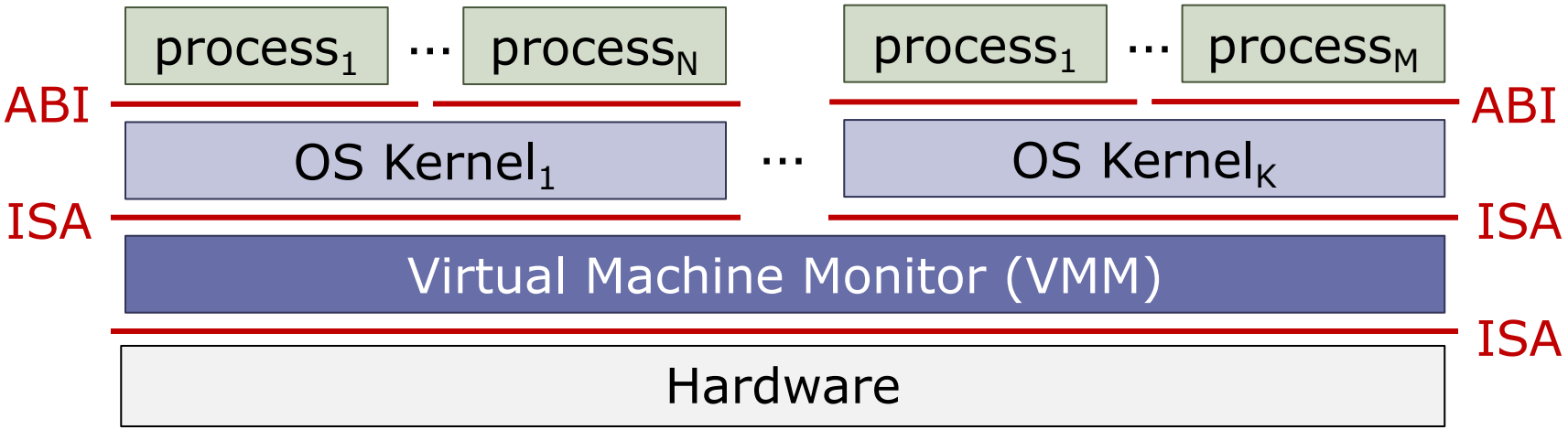

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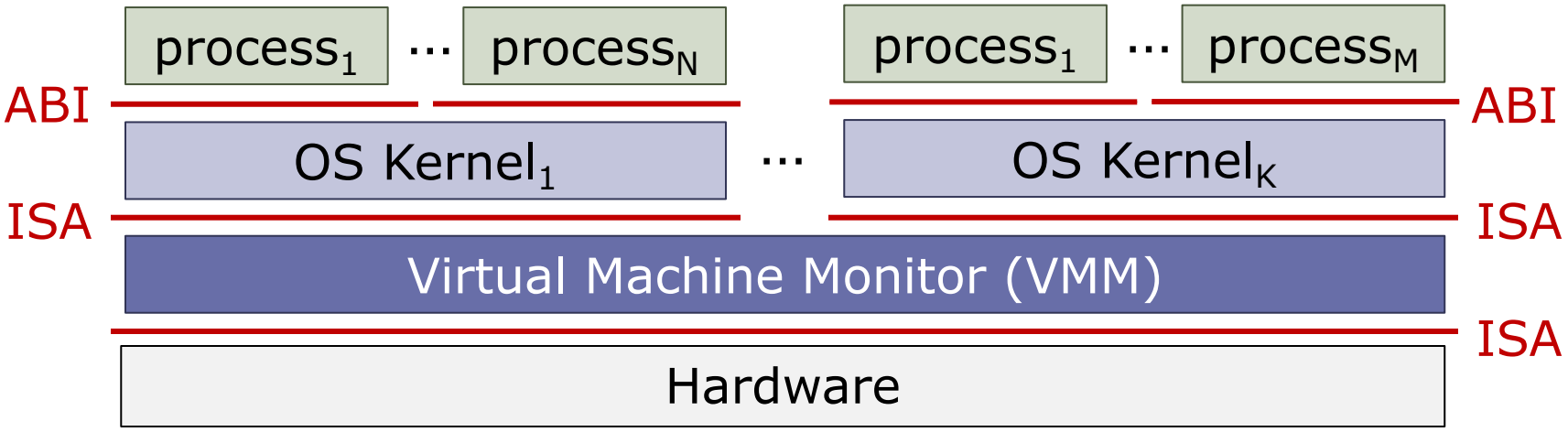


- A VMM (aka Hypervisor) provides a system virtual machine to each OS
- VMM can run directly on hardware (as above) or on another OS
  - Precisely, VMM can be implemented against an ISA (as above) or a process-level ABI. Who knows what lays below the interface…

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.

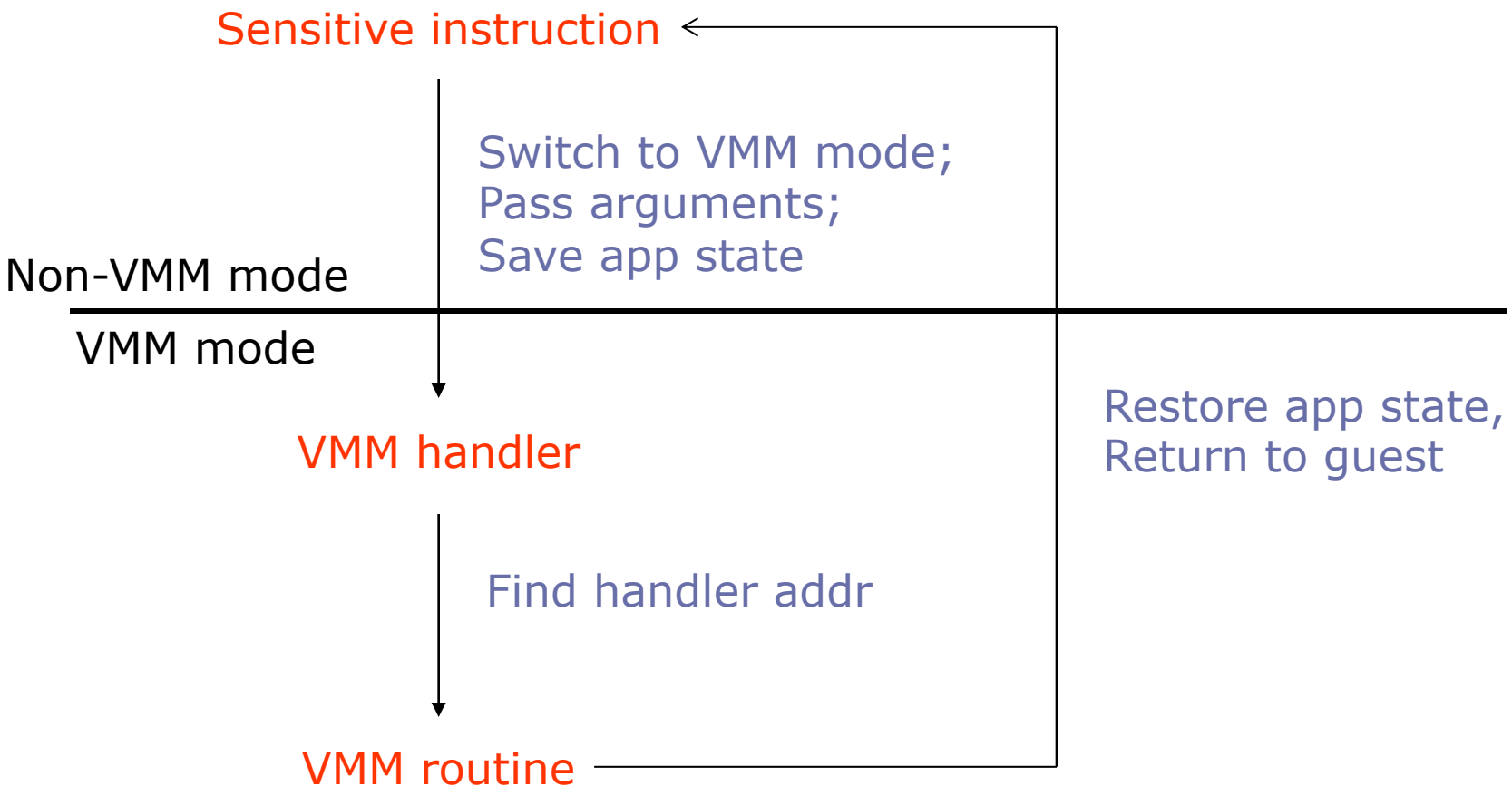
Virtual Machine Requirements
[Popek and Goldberg, 1974]

Classification of instructions into 3 groups:

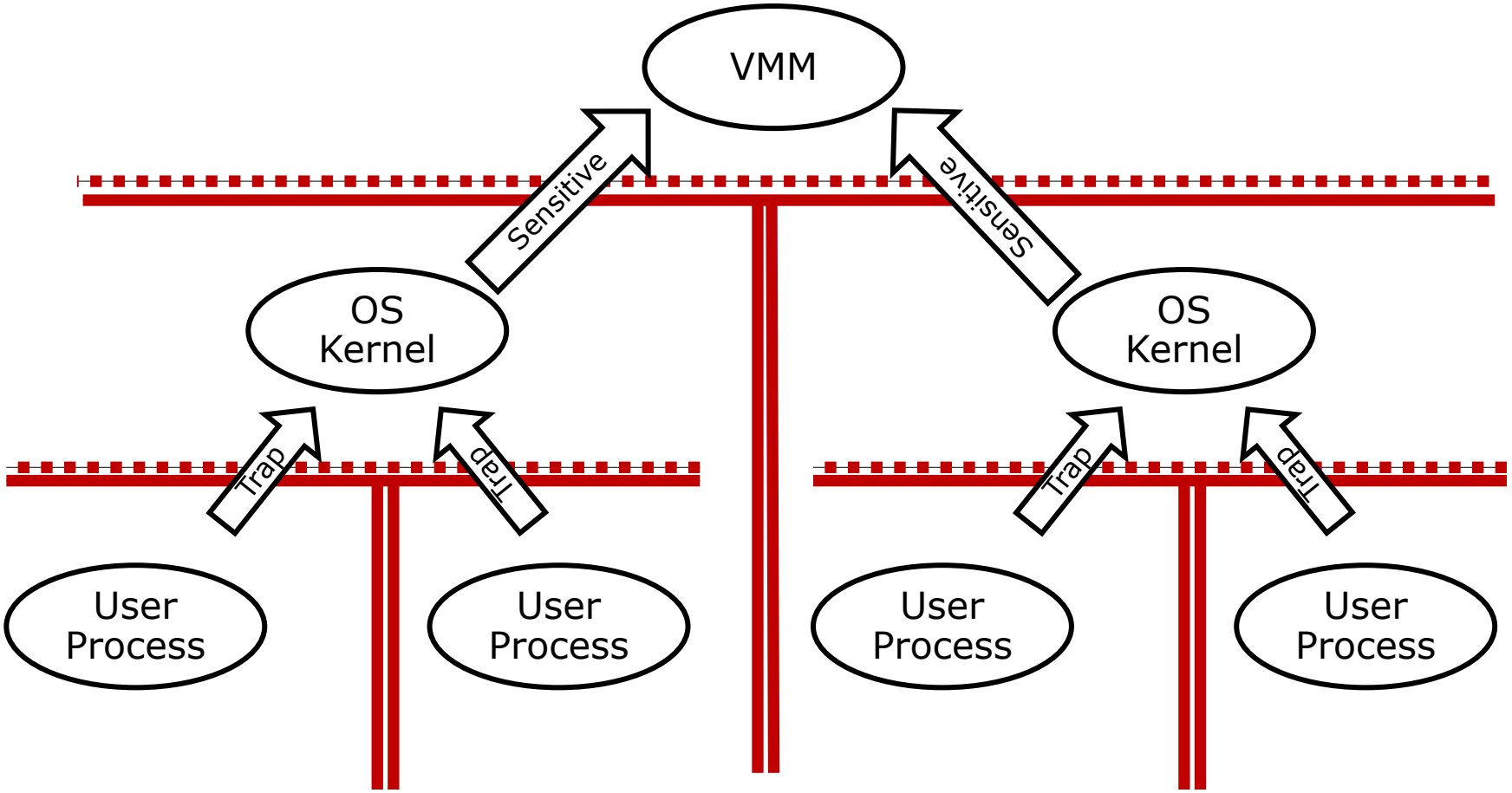
- Privileged instructions: Instructions that trap if the processor is in user mode and do not trap if it is in a more privileged mode.
- Control-sensitive instructions: Instructions that attempt to change the configuration of resources in the system.
- Behavior-sensitive instructions: Those whose behavior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

Sensitive instruction handling



Protection – Multiple OS



Virtual Memory Operations

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- So how expensive are TLB fills?

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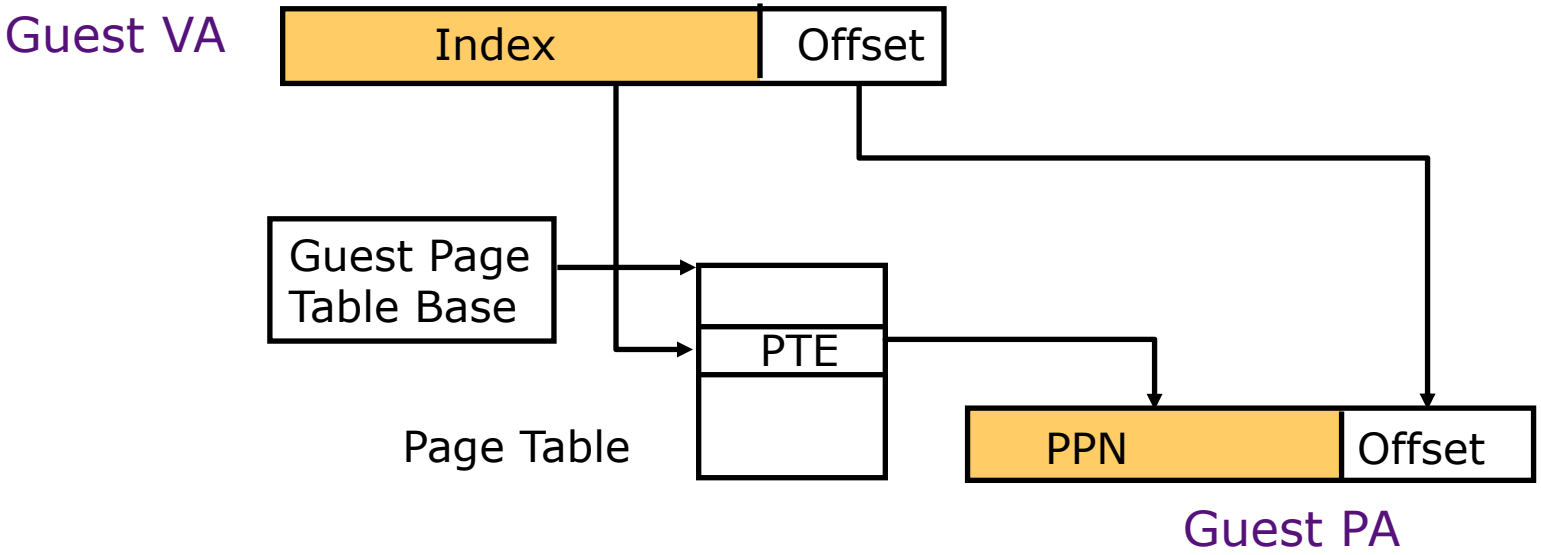

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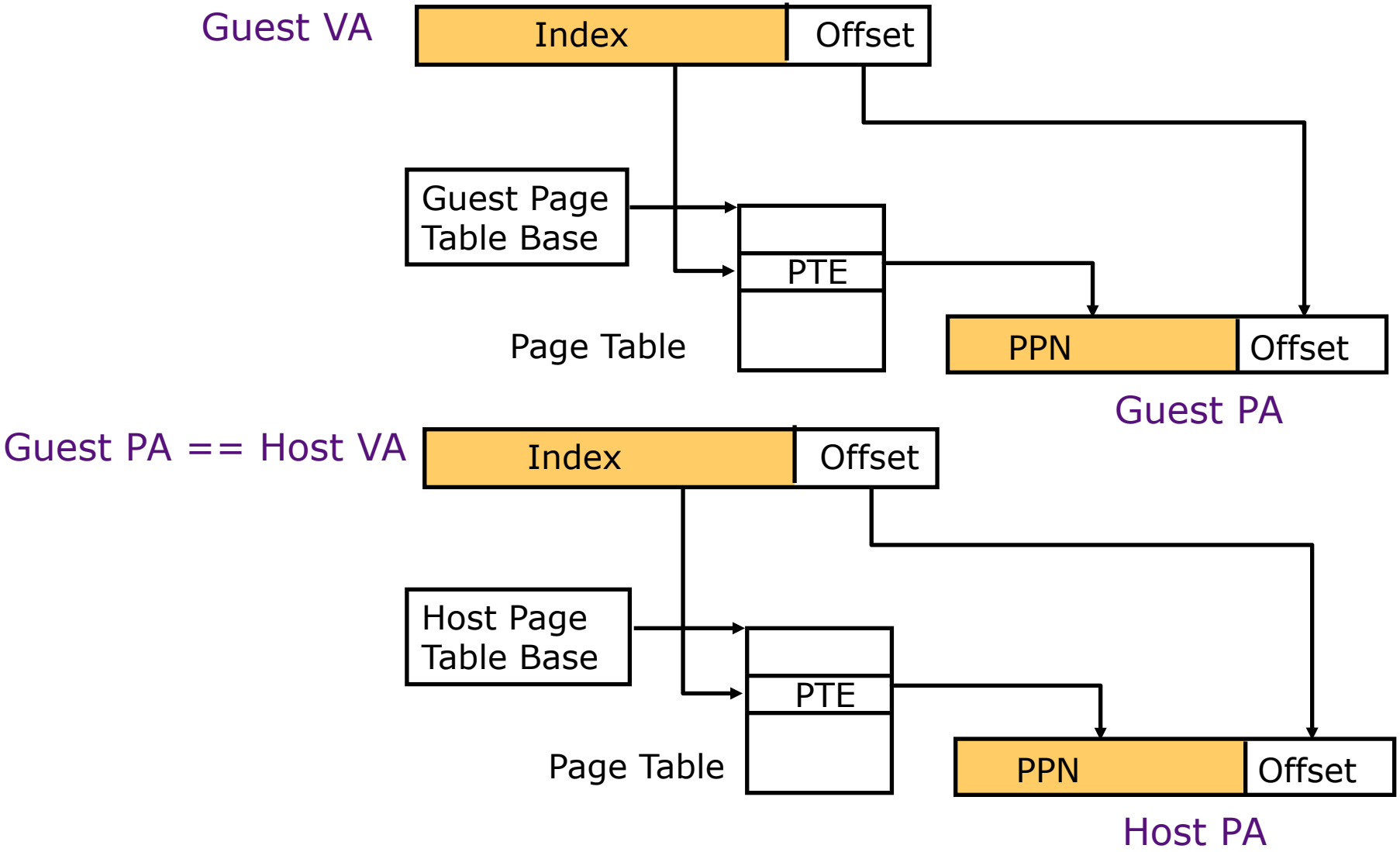

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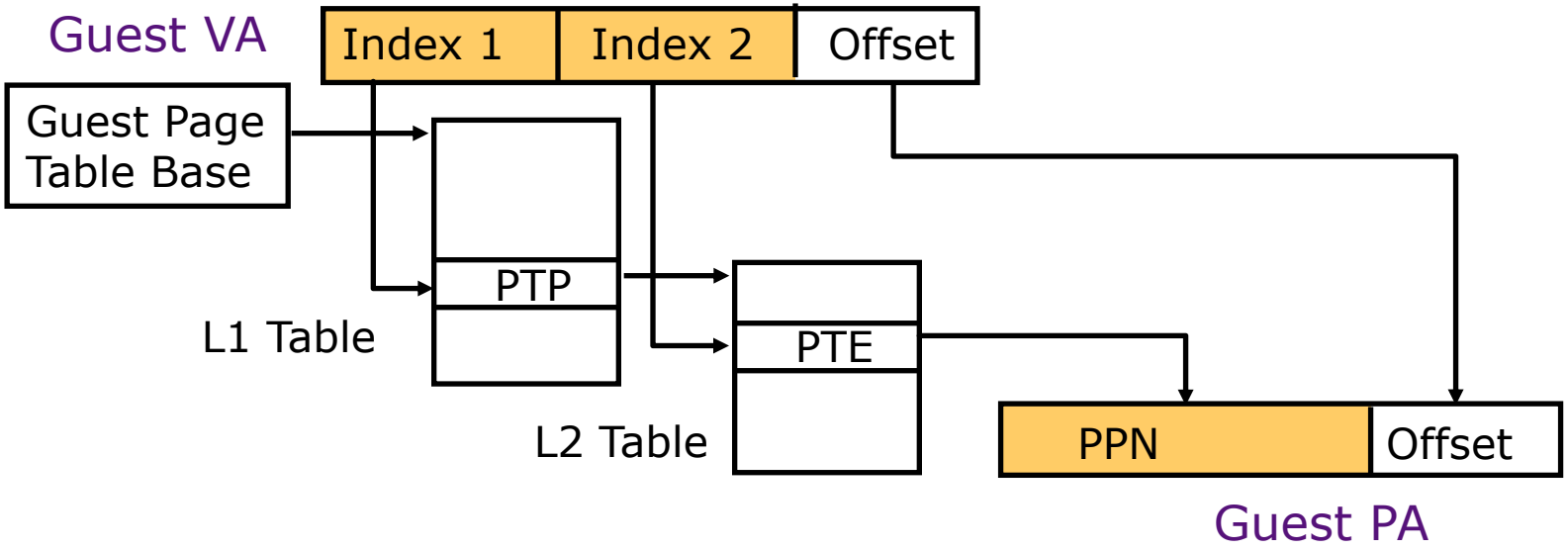

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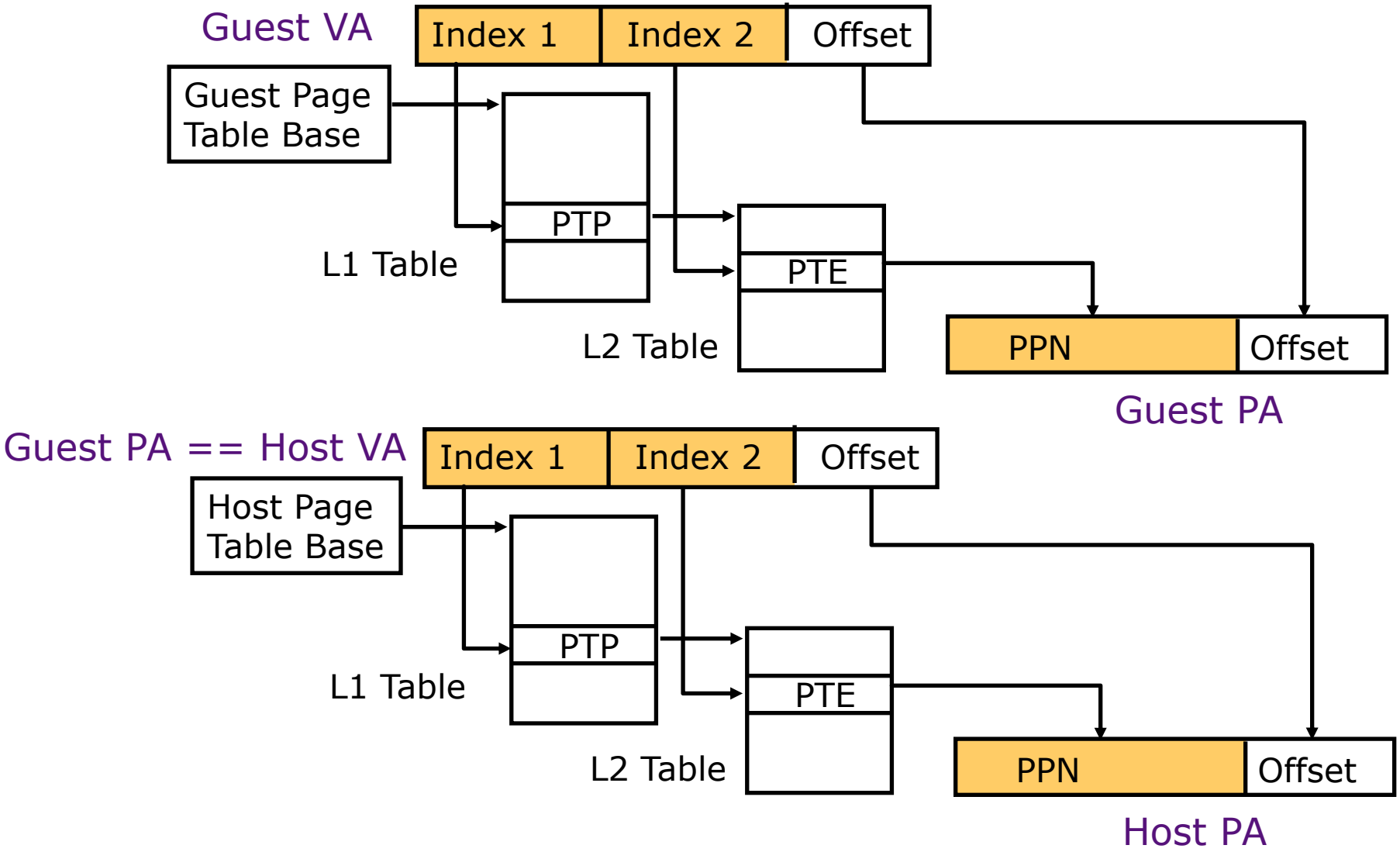

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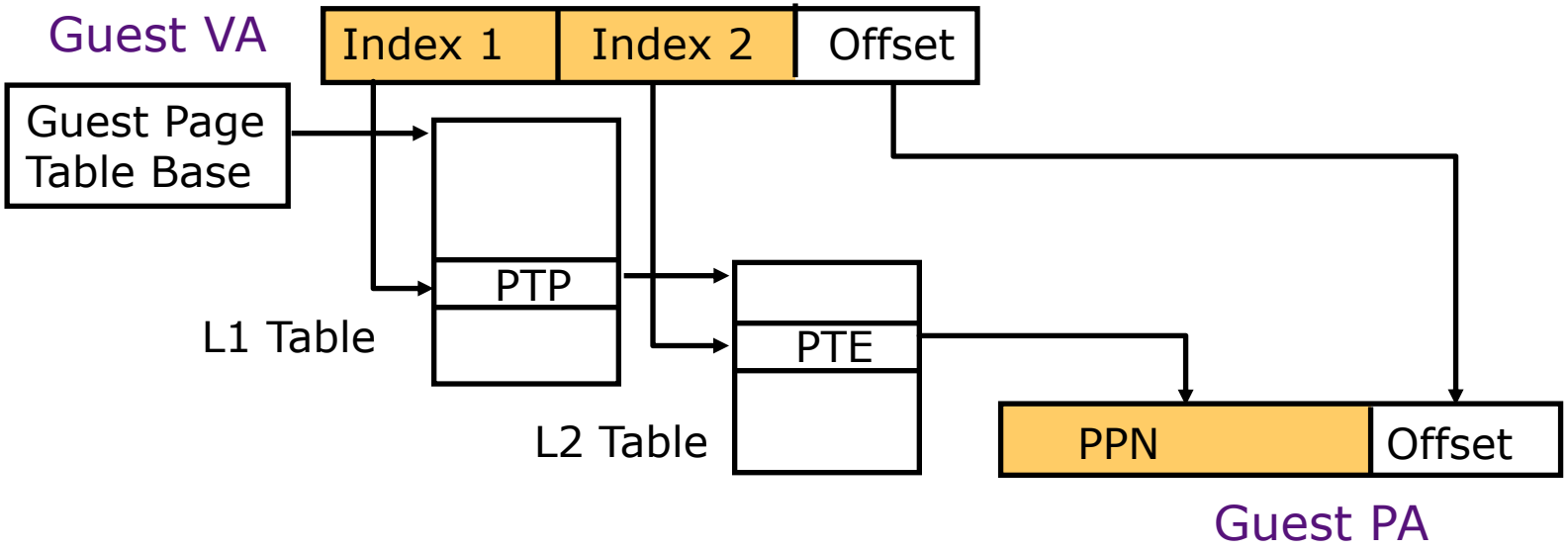

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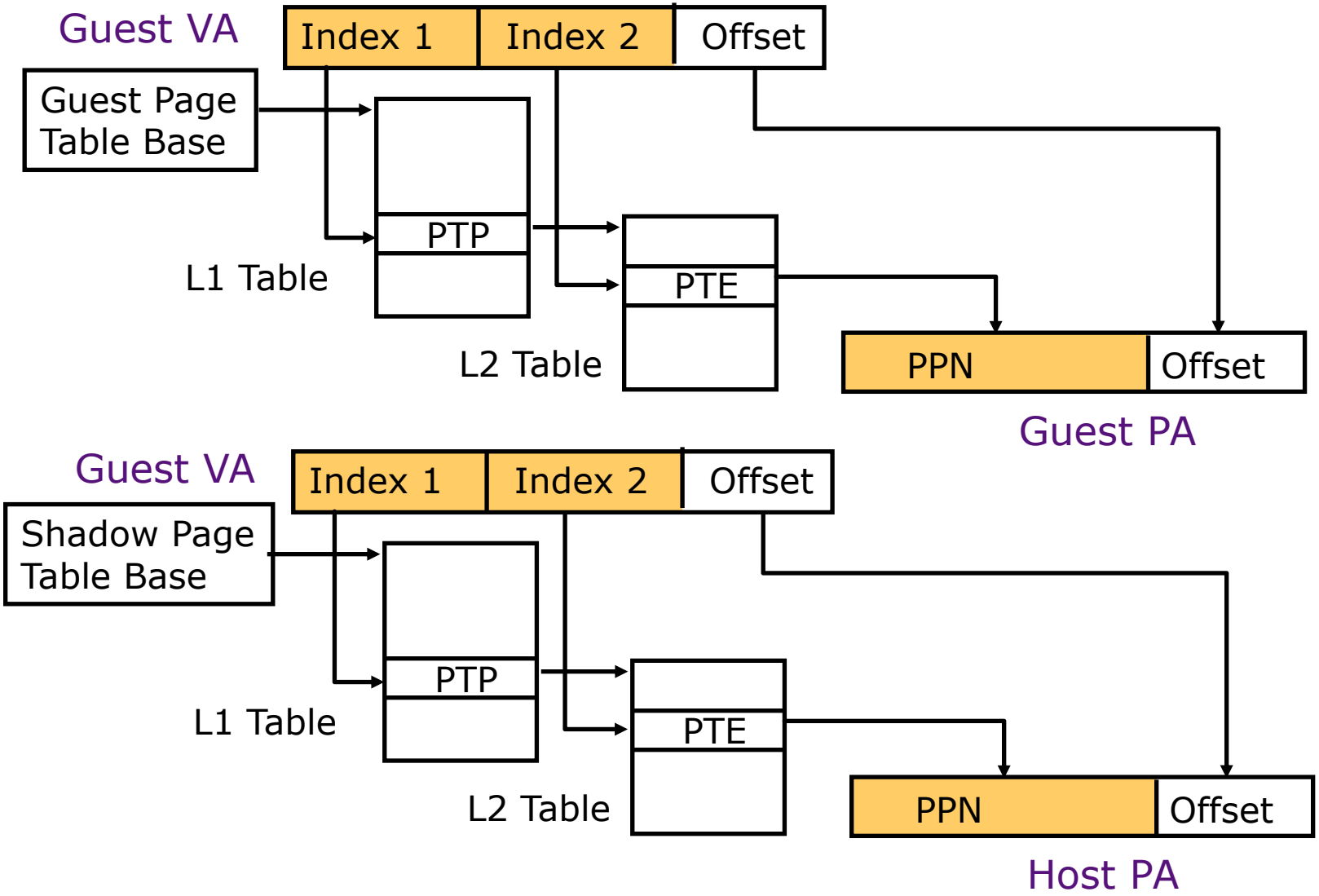
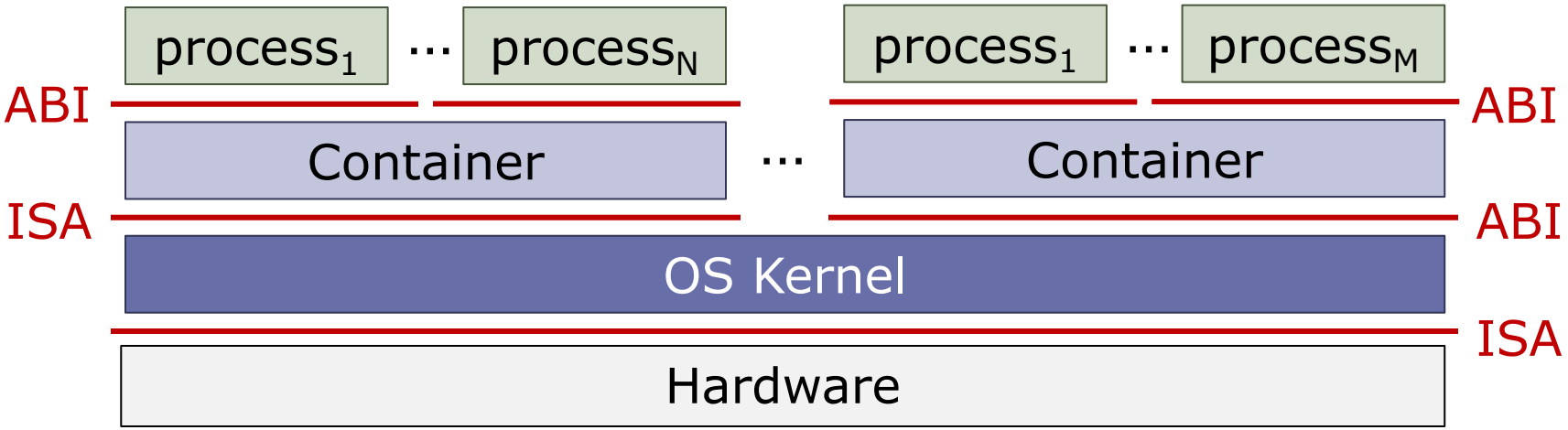


Nested vs Shadow Paging

	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



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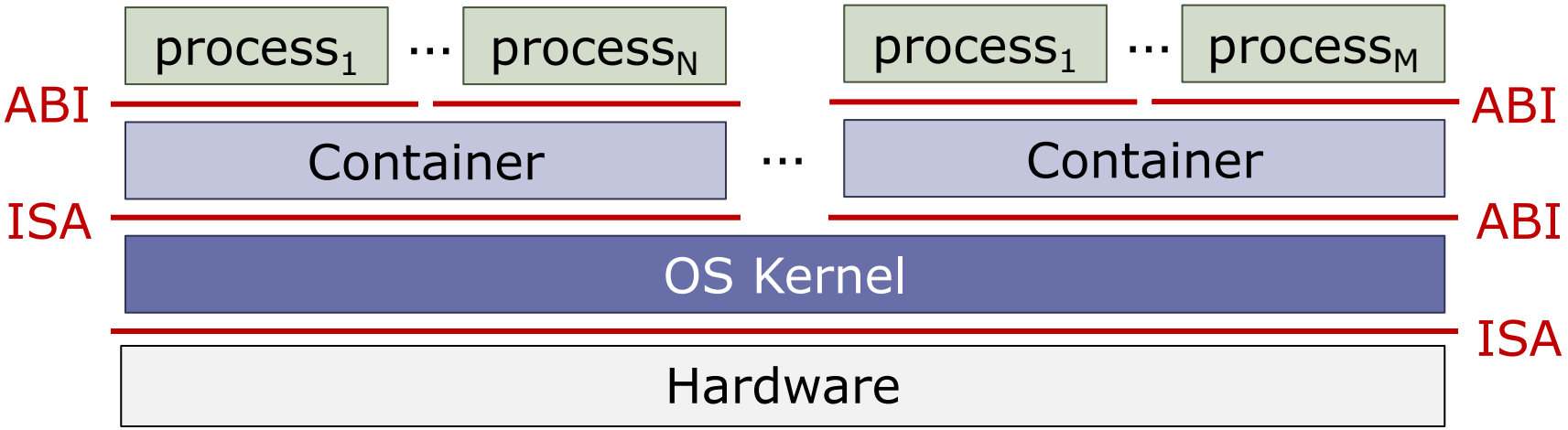

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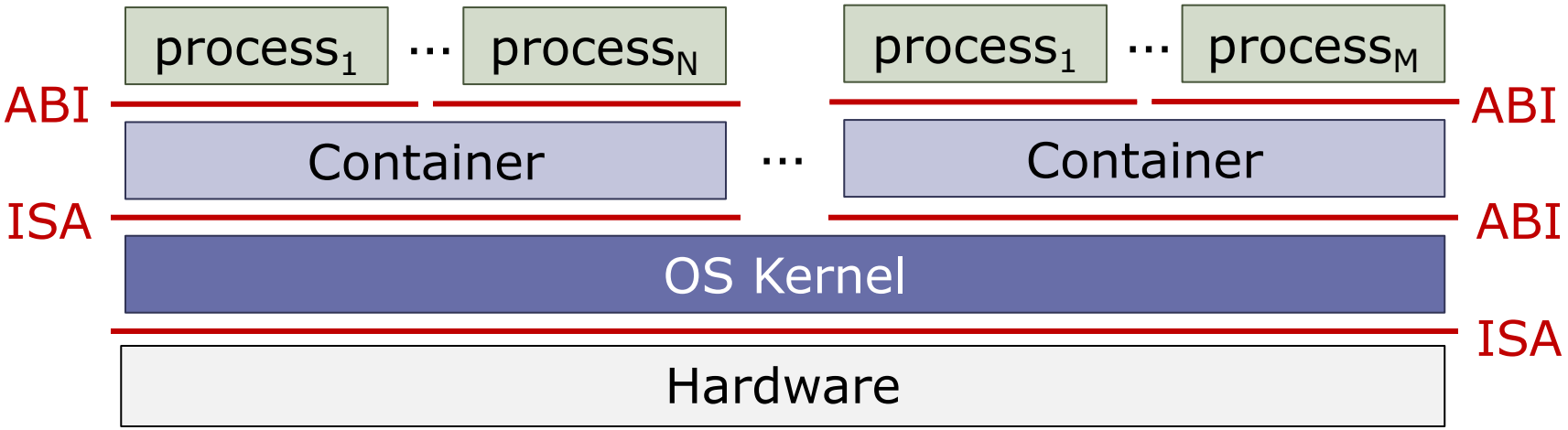

- A "container" provides a process group virtual machine to each set of processes
- Container can run directly on OS, which provides a specific OS ABI to the processes in container

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

Security and Side Channels

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- 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!

Thank you!