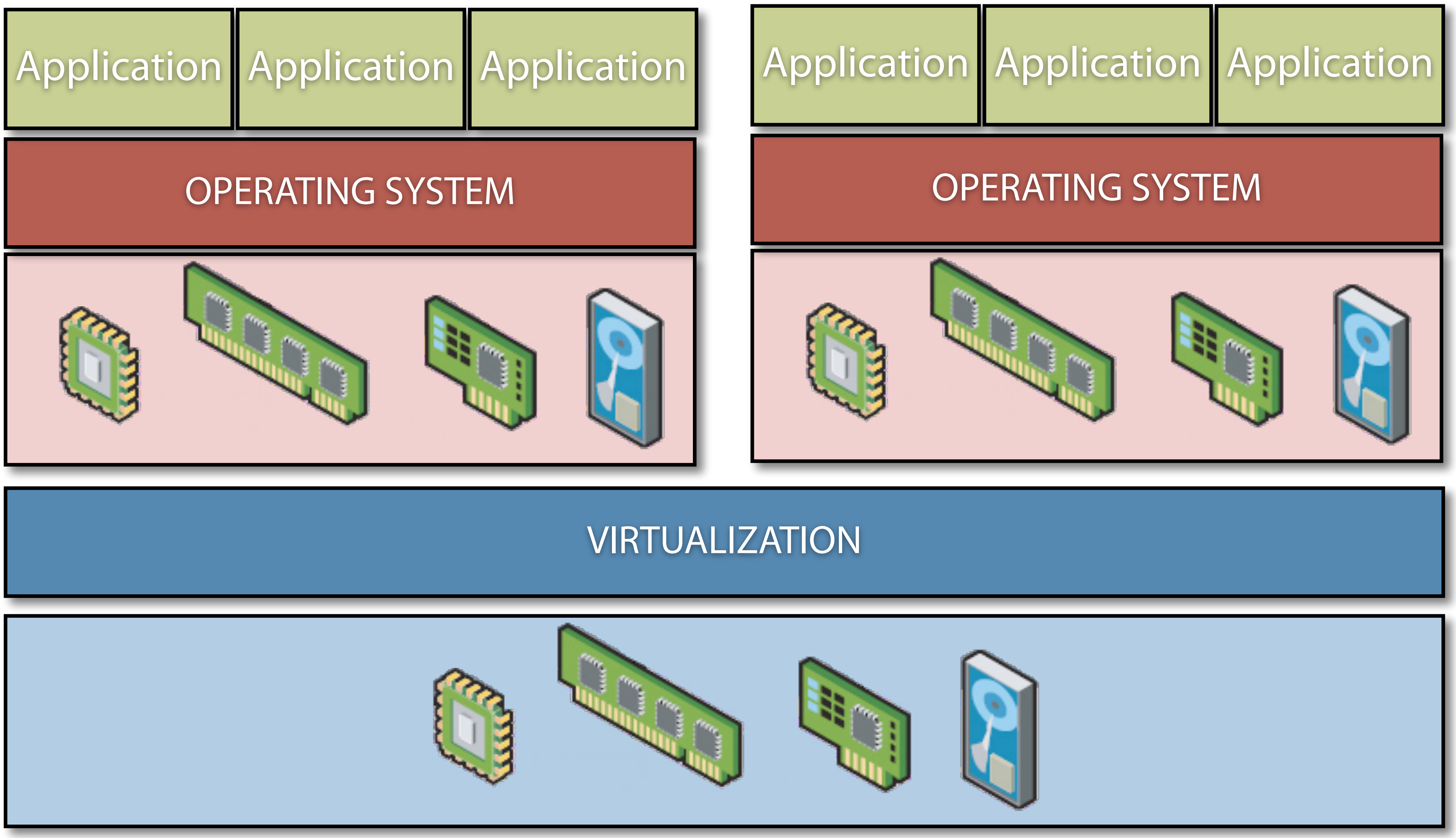
Virtualization



Basic Idea

- **Observation**
  - Hardware resources are typically under-utilized
  - Hardware resources directly relate to cost
- **Goal**
  - Improve hardware utilization
- **How**
  - Share hardware resources across multiple machines
  - May make sense for network attached storage, but what about processor, memory, etc.?
- **Approach**
  - Decouple machine from hardware
- **Virtual Machine** (VM)
  - A machine decoupled from the hardware, i.e. does not necessarily correspond to the hardware
  - Multiple "Virtual Machines" on the same physical host could share the underlying hardware
  - First VM: IBM System/360 Model 40 VM [1965]

Why?

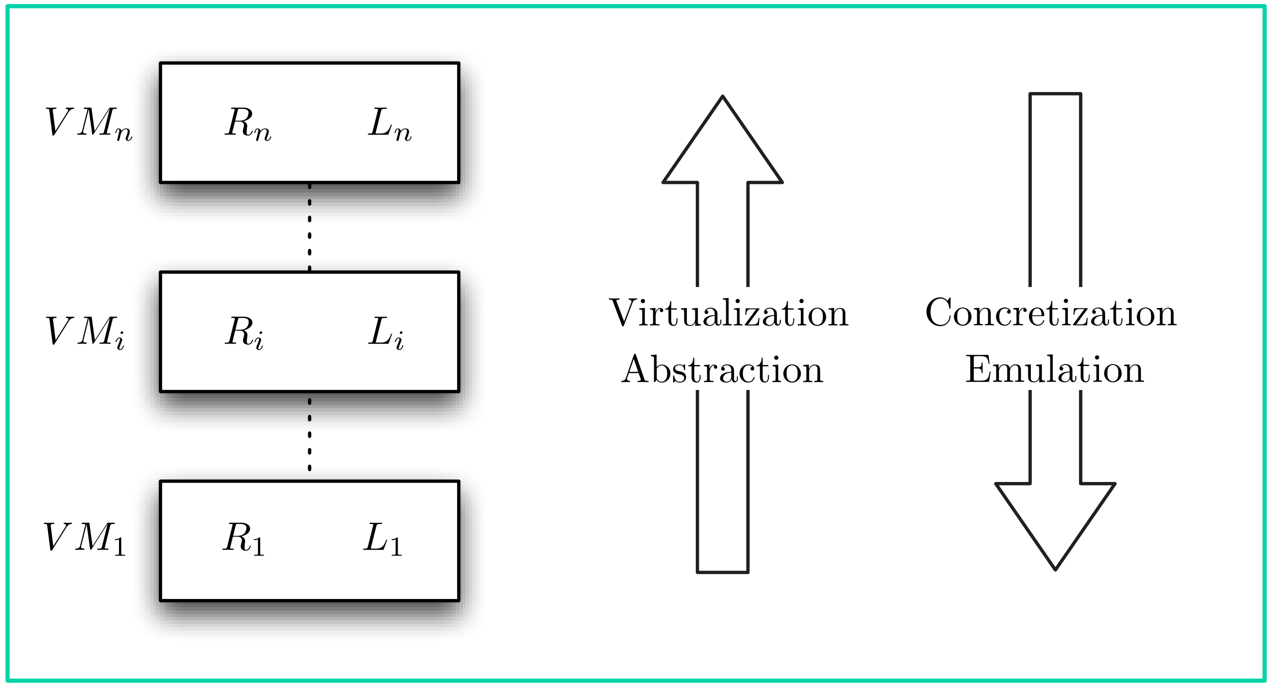
- **Consolidate resources**
  - Server consolidation
  - Client consolidation
- **Improve system management**
  - For both hardware and software
  - From the desktop to the datacenter
- **Improve software lifecycle**
  - Develop, debug, deploy and maintain applications in virtual machines
- **Increase application availability**
  - Fast, automated recovery

Modern Computer Systems

- **Modern computer system is very complex**
  - Hundreds of millions of transistors
  - Interconnected high-speed I/O devices
  - Networking infrastructures
  - Operating systems, libraries, applications
  - Graphics and networking software
- **To manage this complexity: Levels of Abstractions**
  - Allows implementation details at lower levels of design to be ignored or simplified
  - Each level is separated by well-defined interfaces, so that the design of a higher level can be decoupled from the lower levels

Layers of Abstraction

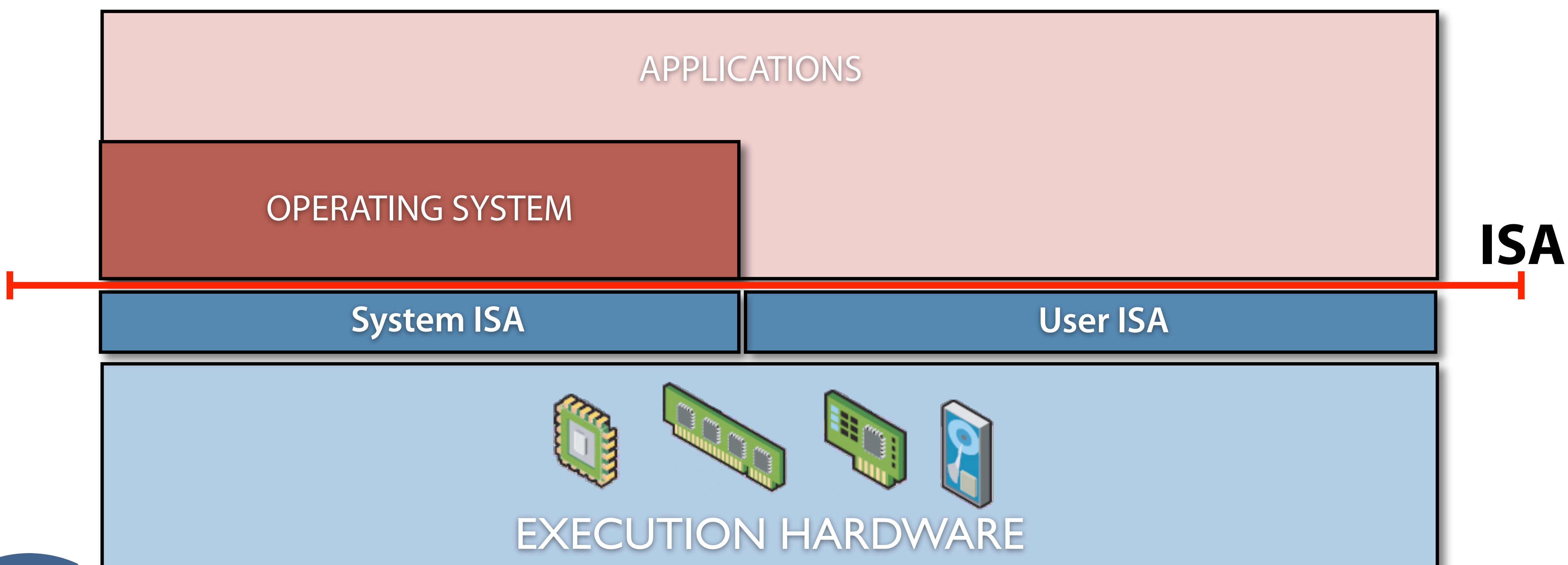
- **Abstraction**
  - used to manage complexity
  - typically defined in layers (VMi)
  - each layer has its own language (Li) and data structures (Ri)
  - lowest layers implemented in hardware
  - higher layers implemented in software
- **Machine: denotes the system on which software is executed.**
  - to an operating system this is generally the physical system
  - to an application program a machine is defined by the combination of hardware and OS-implemented abstractions



- **Typical Layers**
  - VM4: Applications
  - VM3: Operating System
  - VM2: Assembler Machine
  - VM1: Firmware Machine
  - VM0: Hardware Machine

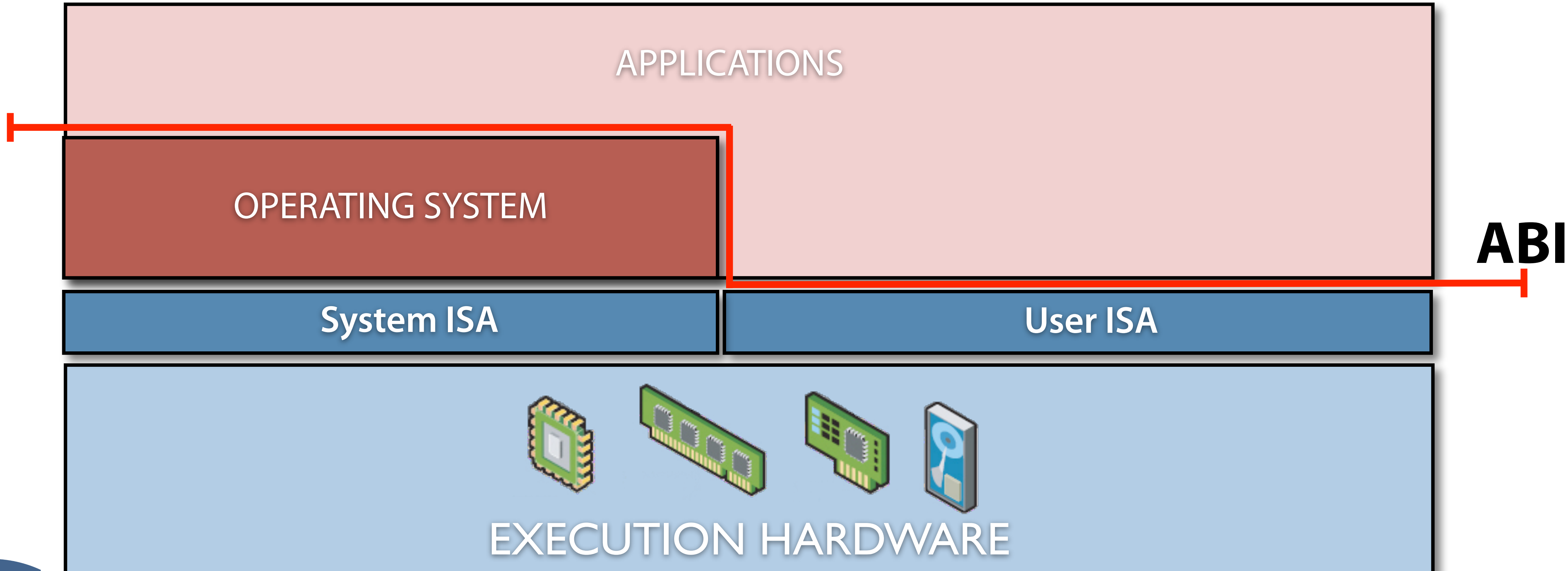
Machine Level Abstraction

- **Instruction Set Architectures (ISA)**
  - Defines hardware/software boundary
  - **User ISA**: portion of architecture visible to an application programmer
  - **System ISA**: portion of architecture visible to the supervisor software (i.e., OS)
- **For OS developers, a machine is defined by ISA**



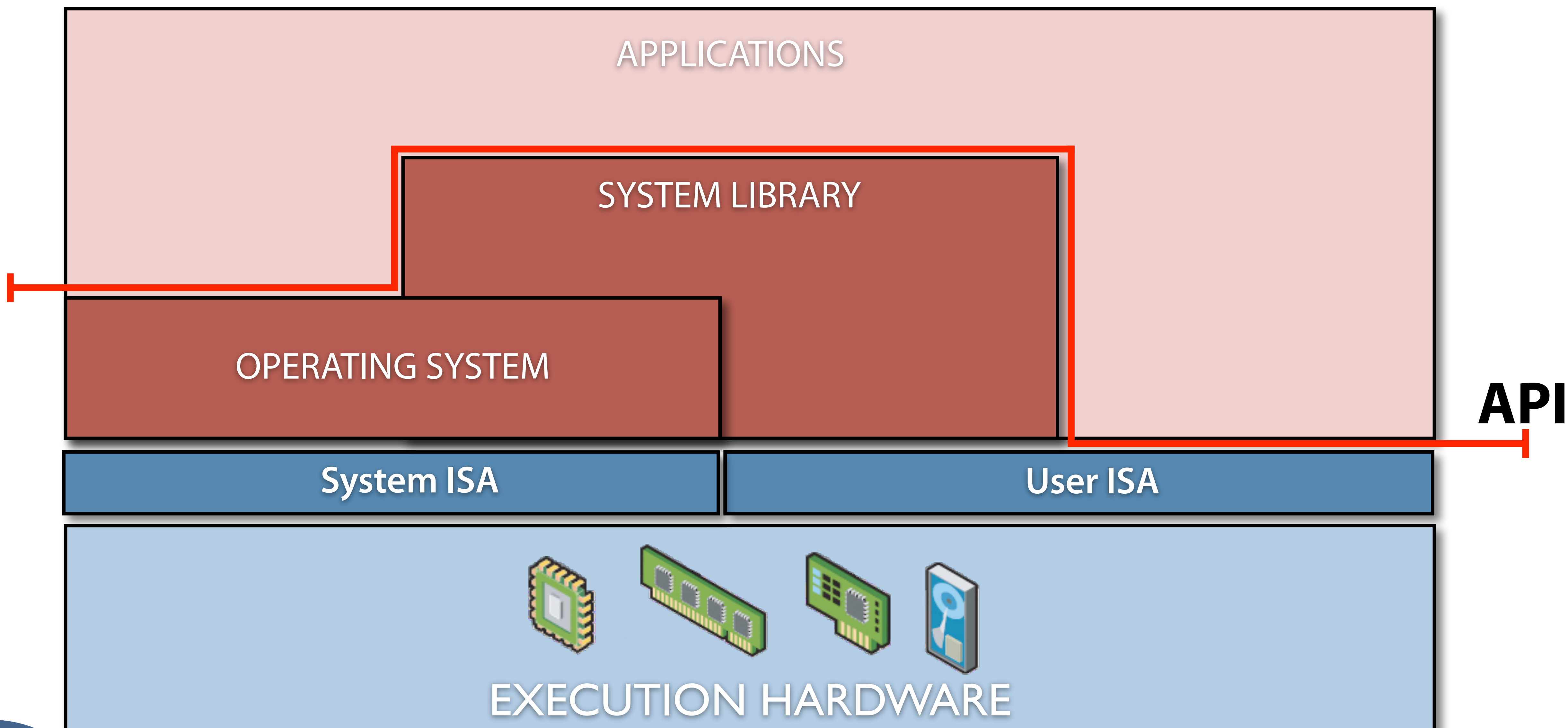
OS Level Abstraction

- **Application Binary Interface (ABI)**
  - Defines program interface to hardware resources and services
  - **User ISA**
    - System instructions are not included in the ABI
    - User instructions allow program to direct access hardware
  - **System calls**
    - Indirect interface for accessing shared system resources and services
    - implemented by the supervisor software
- **For compiler/library developers, a machine is defined by ABI**



Application Level Abstraction

- **Application Programming Interface (API)**
  - Defined in terms of an high level language (e.g., C)
  - Typically implemented as a system library (e.g., libc)
- **For application developers , a machine is defined by API**



What is a machine?

- A machine is an entity that provides an interface
  - **Program** view:

    Machine = Entity that provides the API
  - **Process** view:

    Machine = Entity that provides the ABI
  - **Operating system** view:

    Machine = Entity that provides the ISA

What is a virtual machine?

- Virtual machine is an entity that emulates a guest interface on top of a host machine
  - **Program** view:

    Virtual machine = Entity that emulates an API on top of another

    Virtualizing software = compiler/interpreter
  - **Process** view:

    Virtual Machine = Entity that emulates an ABI on top of another

    Virtualizing software = runtime
  - **Operating system** view:

    Virtual Machine = Entity that emulates an ISA

    Virtualizing software = virtual machine monitor (VMM)

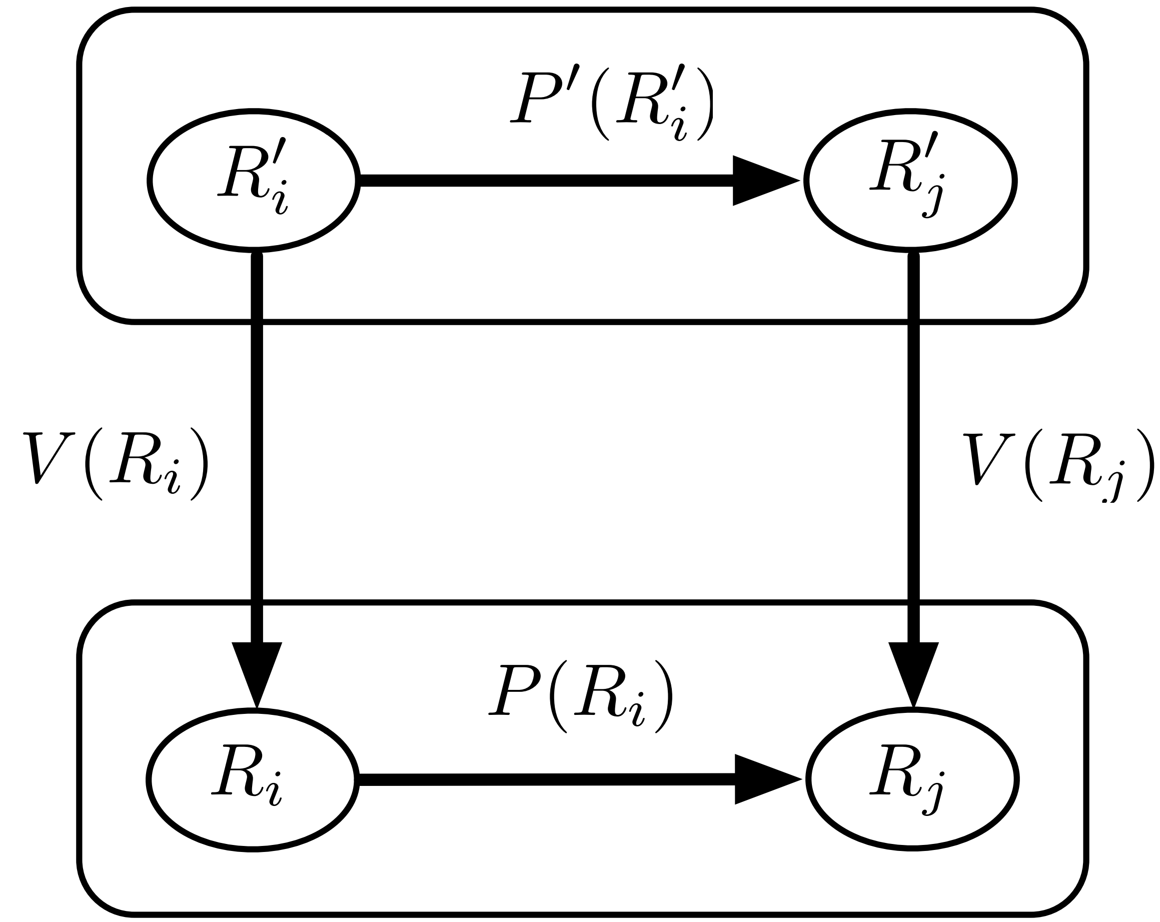
Formal Definition

- Virtualization is defined as the construction of an isomorphism that maps a **guest** machine to an existing **host** machine such that:
  - maps the guest state R_i (collection of guest virtualization objects) onto the host state R_i' through some function V() such that

$$V(R_i) = R_i'$$

  - for every policy P() transforming the state R_i in state R_j in the guest, there is a corresponding policy P'() in the host that performs an equivalent modification of the host state

$$P' \circ V(R_i) = V \circ P(R_i)$$

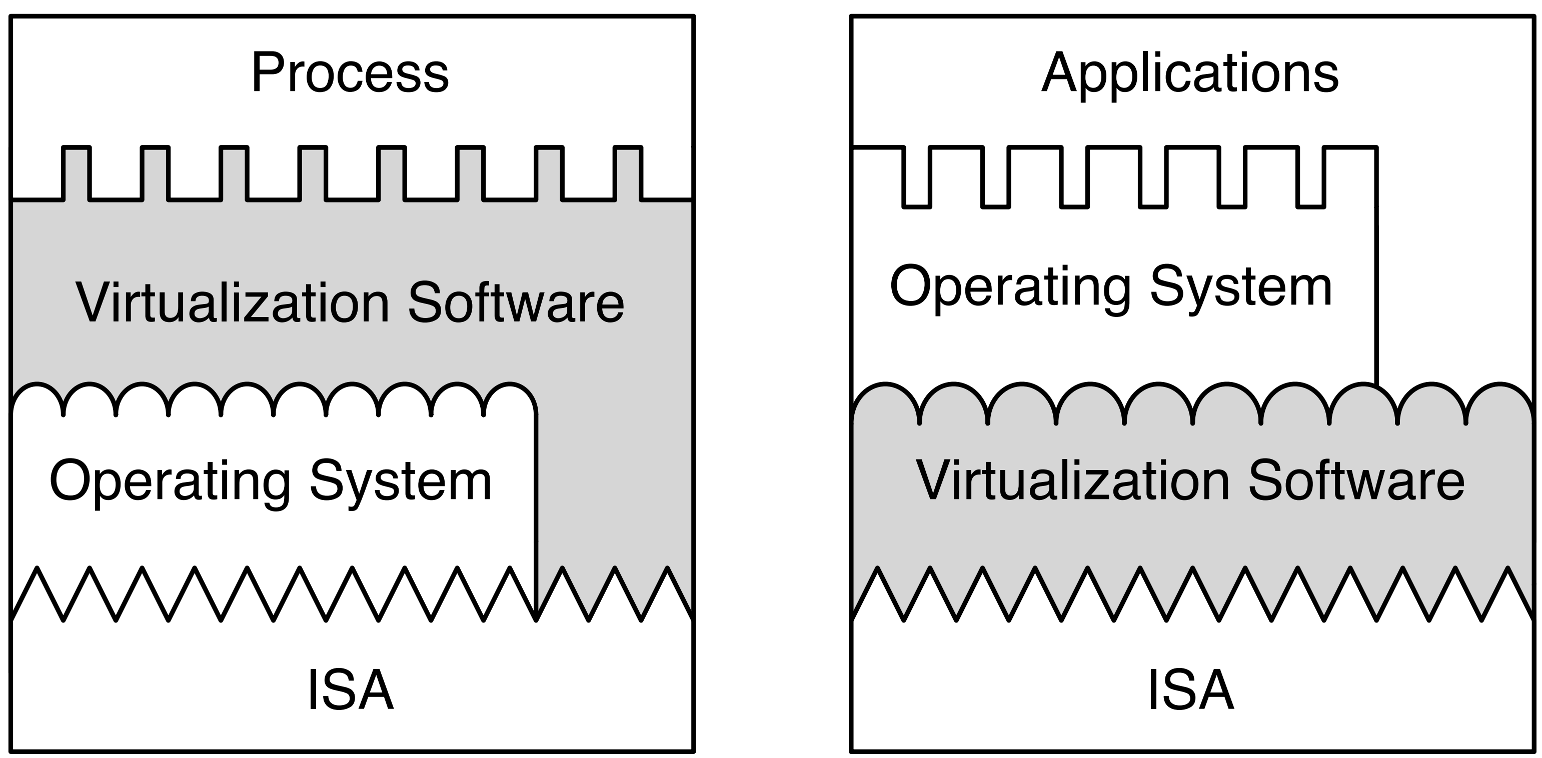


Perspectives

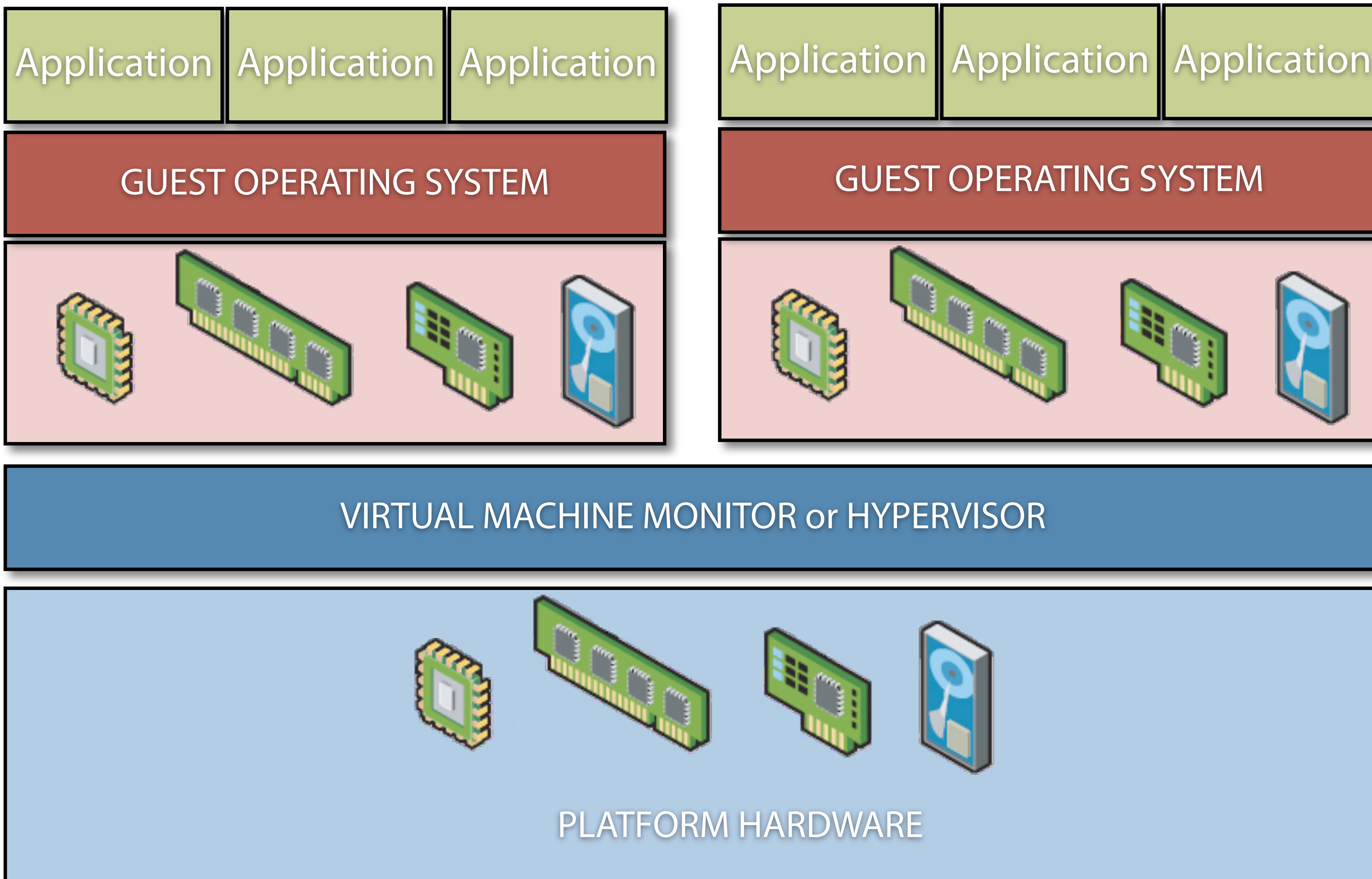
- ***Process perspective*:** the system ABI defines the interface between the process and machine
  - user-level hardware access: logical memory space, user-level registers and instructions
  - OS mediated: Machine I/O or any shared resource or operations requiring system privilege.
- ***Operating system perspective*:** ISA defines the interface between OS and machine
  - system is defined by the underlying machine
  - direct access to all resources
  - manage sharing
- Virtual machine executes software (process or operating system) in the same manner as target machine
  - Implemented with both hardware and software
  - VM resources may differ from that of the physical machine
  - Generally not necessary for VM to have equivalent performance

Where is the VM?

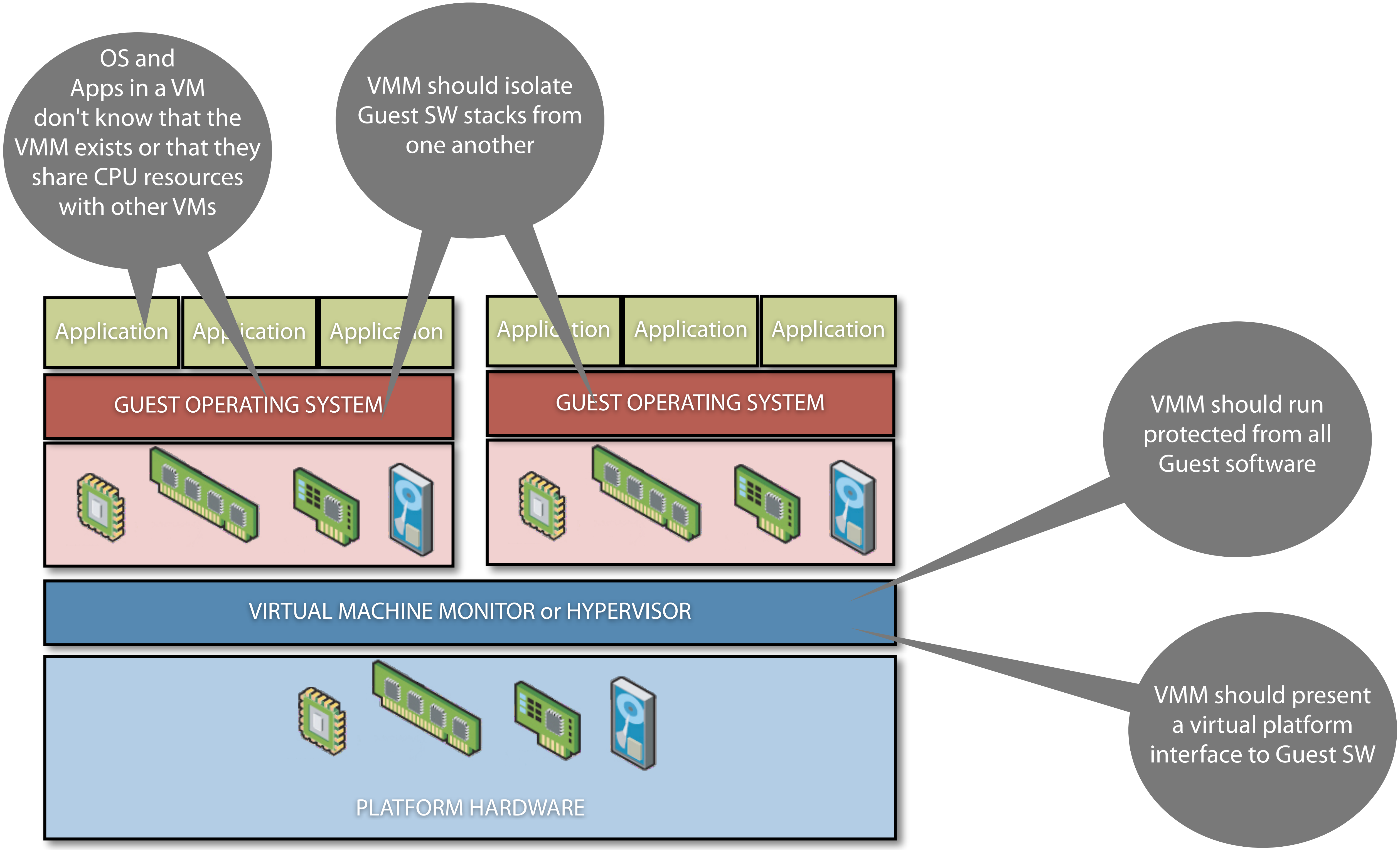
- ***Process virtual machine*:** supports an individual process
  - Emulates user-level instructions and operating system calls
  - Virtualizing software placed at the ABI layer
- ***System Virtual Machines*:** emulates the target hardware ISA
  - guest and host environment may use the same ISA
- Virtual Machines are implemented as combination of
  - Real hardware
  - Virtualizing software



Virtual Machine Monitor

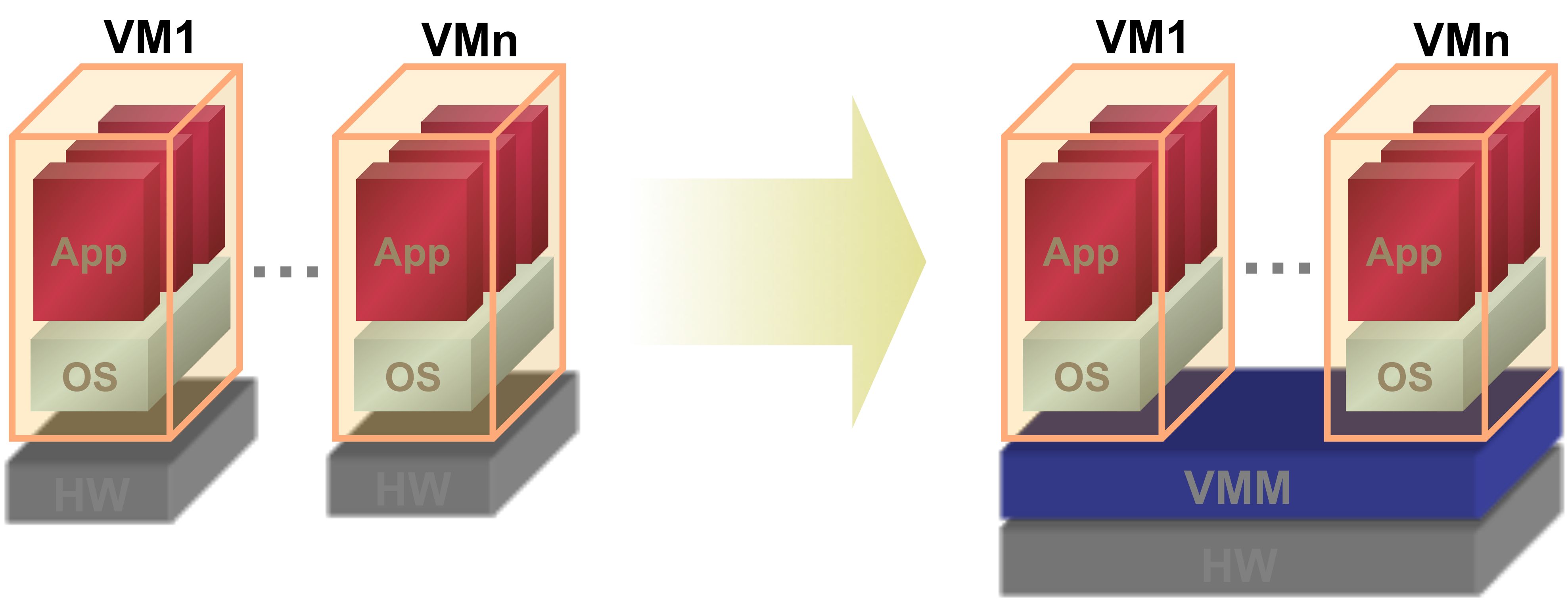


VMM Challanges



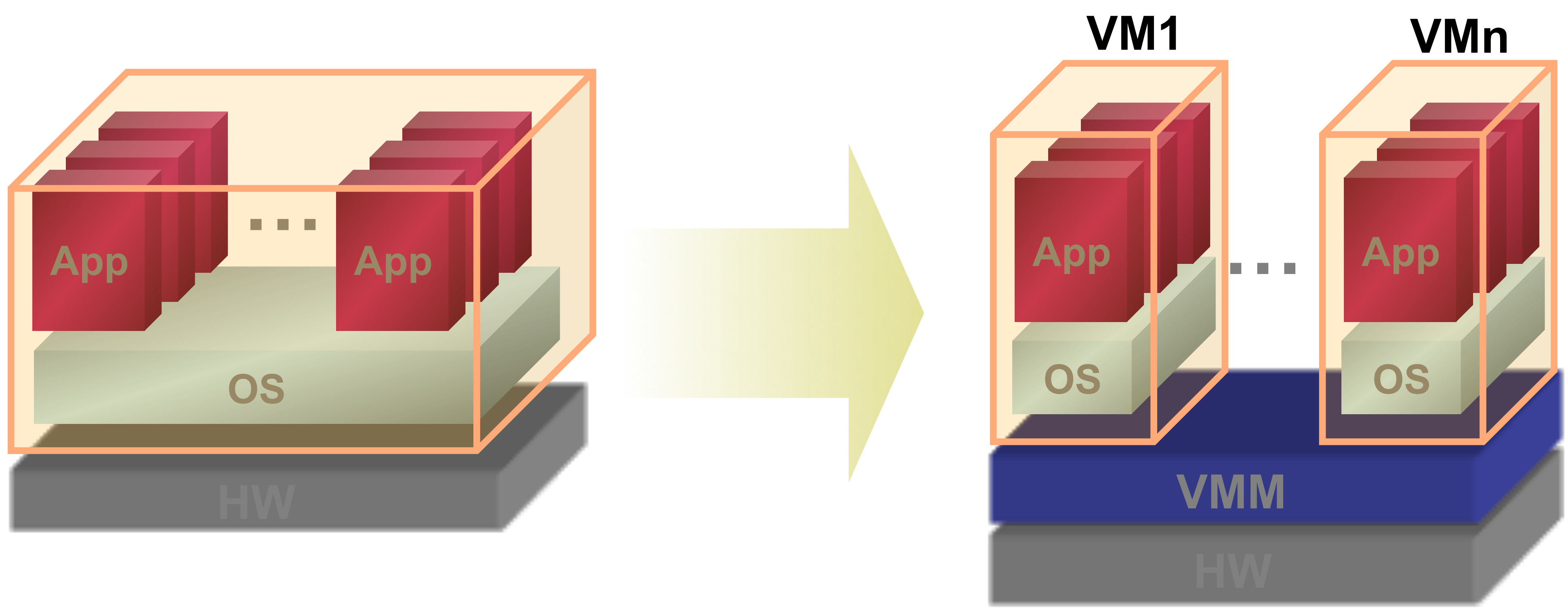
VM Usage: Workload Consolidation

- Server virtualization consolidates many systems onto one physical platform
- Pros
  - Each application can run in a separate environment delivering true isolation
  - Cost Savings: power, space, cooling, hardware, software and management
  - Ability to run legacy applications in legacy OSs
  - Ability to run through emulation legacy applications in legacy HW
- Cons
  - Disk and memory footprint increase due to multiples OSs
  - Performance penalty caused by resource sharing management



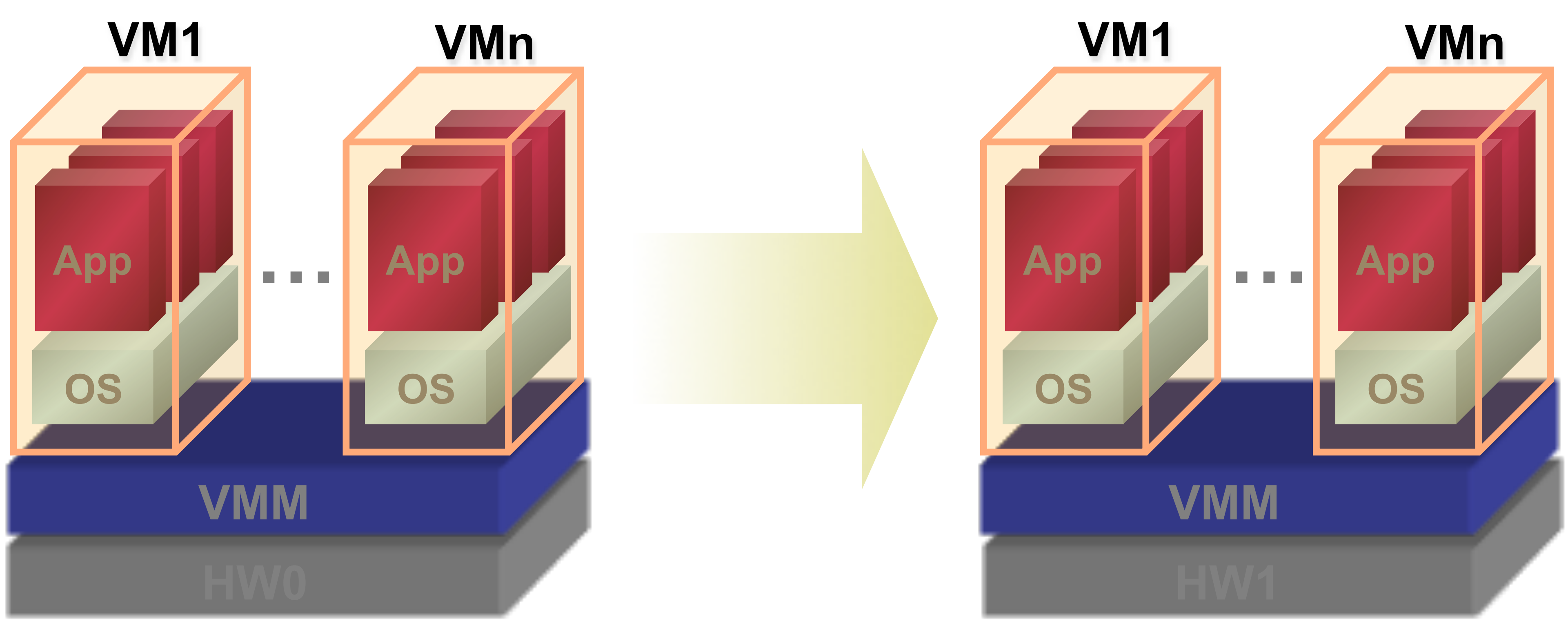
VM Usage: Workload Isolation

- Virtualization can improve overall system security and reliability by isolating multiple software stacks in their own VMs
  - Security: intrusions can be confined to the VM in which they occur
  - Reliability: software failures in one VM do not affect the other VMs
  - As a side effect, if the hypervisor or drivers are compromised, the whole VMs can be compromised (equivalent to BIOS attack)



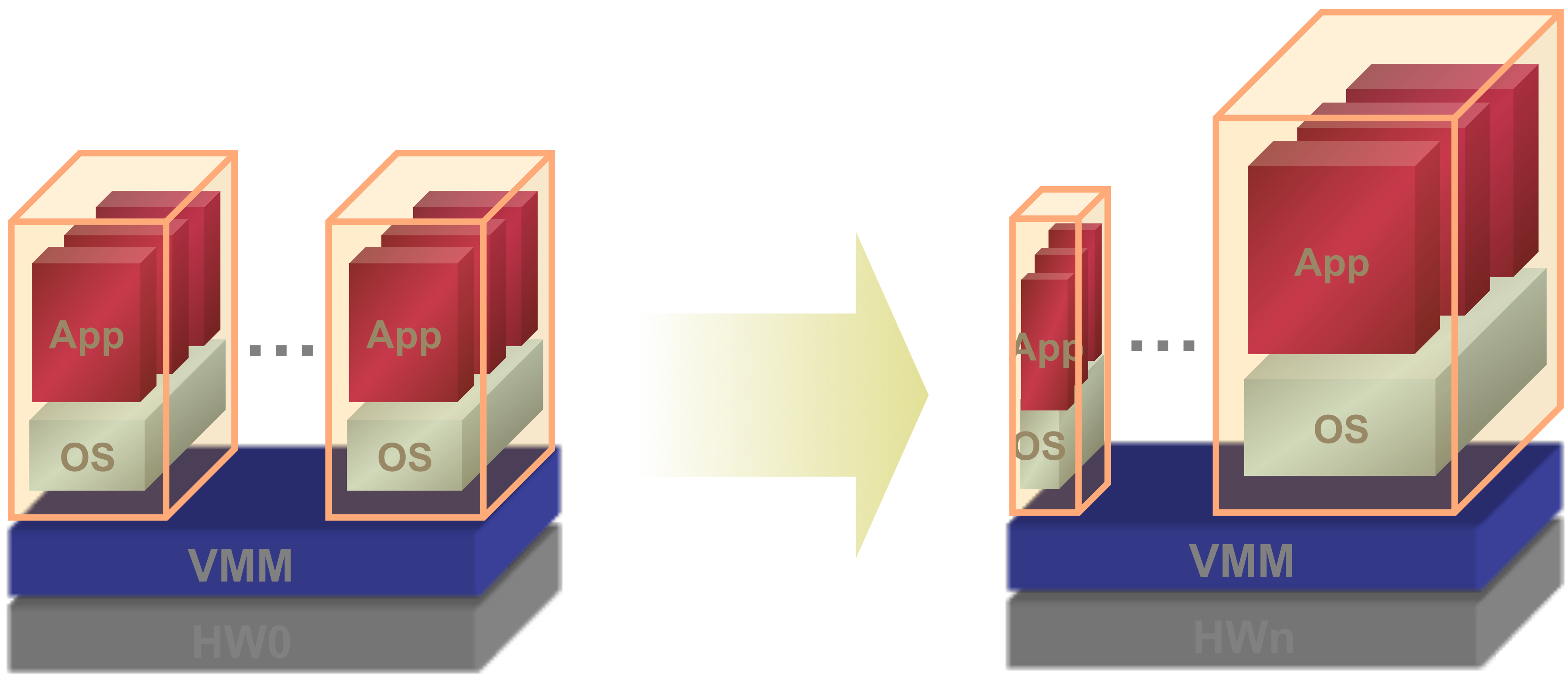
VM Usage: Workload Isolation (I)

- Migrate (move) running VMs to a different platform
  - It facilitates hardware maintenance operations
  - Both at server and data-center level
  - High Availability: if an application goes down, it is not necessary to wait for the reboot of the operating system/application



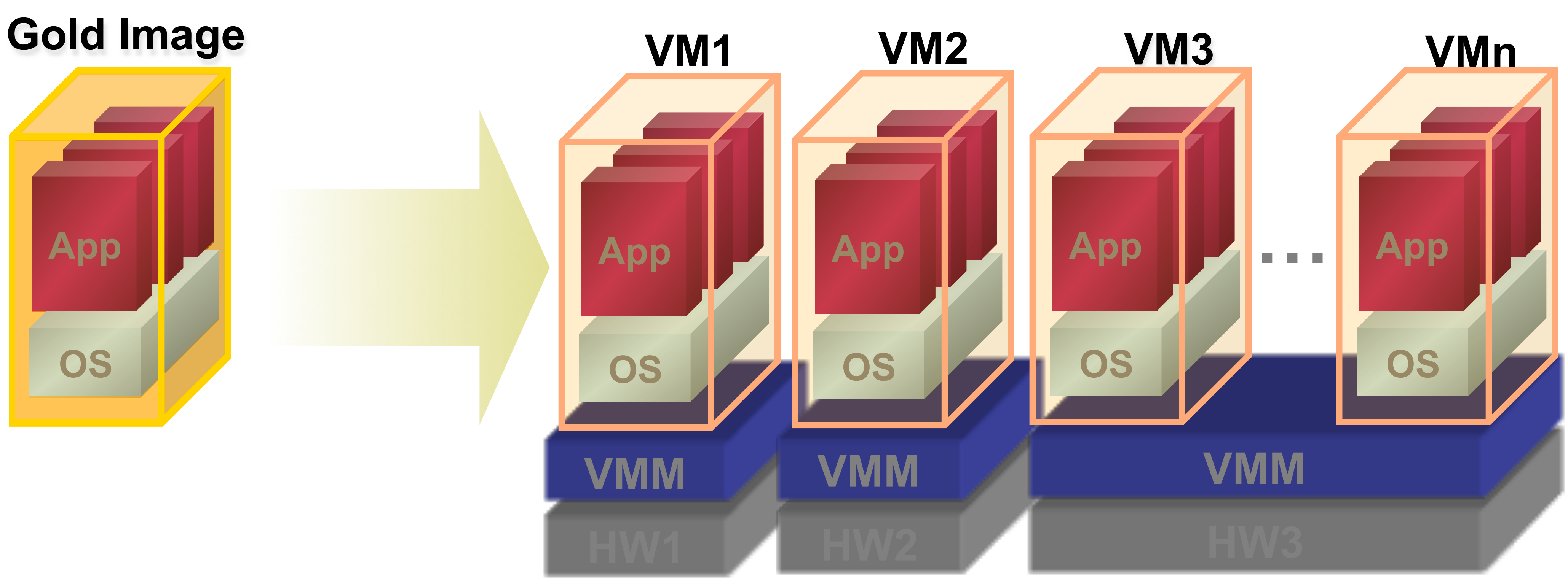
VM Usage: Workload Isolation (II)

- Migrate (move) running VMs to a different platform
  - Resources can be adjusted dynamically
  - VM migration can be triggered automatically by workload balancing or failure-prediction agents
  - If a given application needs more resources, it could be easily moved to other physical host with more power



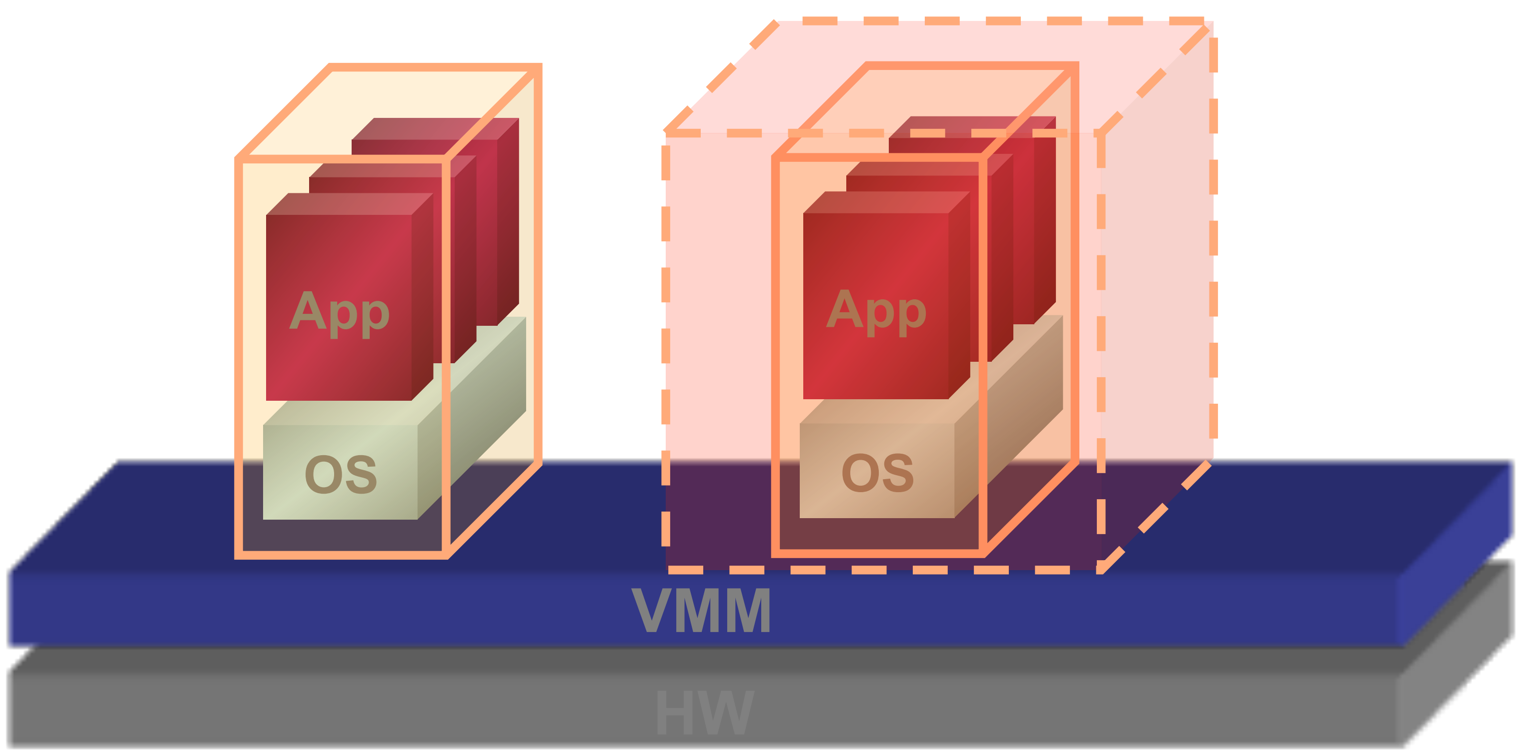
VM Usage: Fast Deployment

- Service providers usually offer some standard services
  - Standard images can be provided instantaneously
  - Simplifies deployment procedures: everything is stored in a file that represents the VM
  - Easier backward compatibility (Gold Image 1, 2, 3, etc)

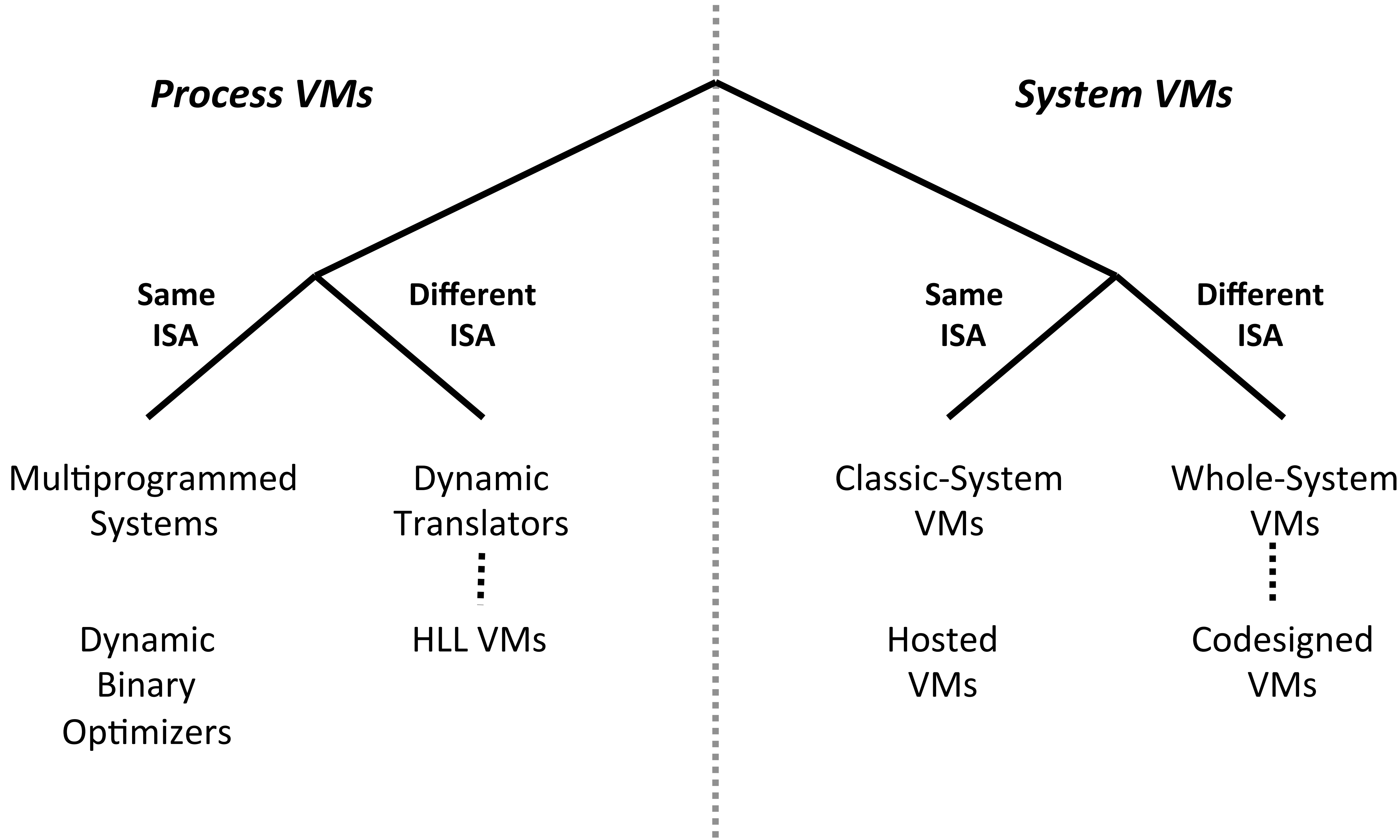


VM Usage: Testing and Develpment

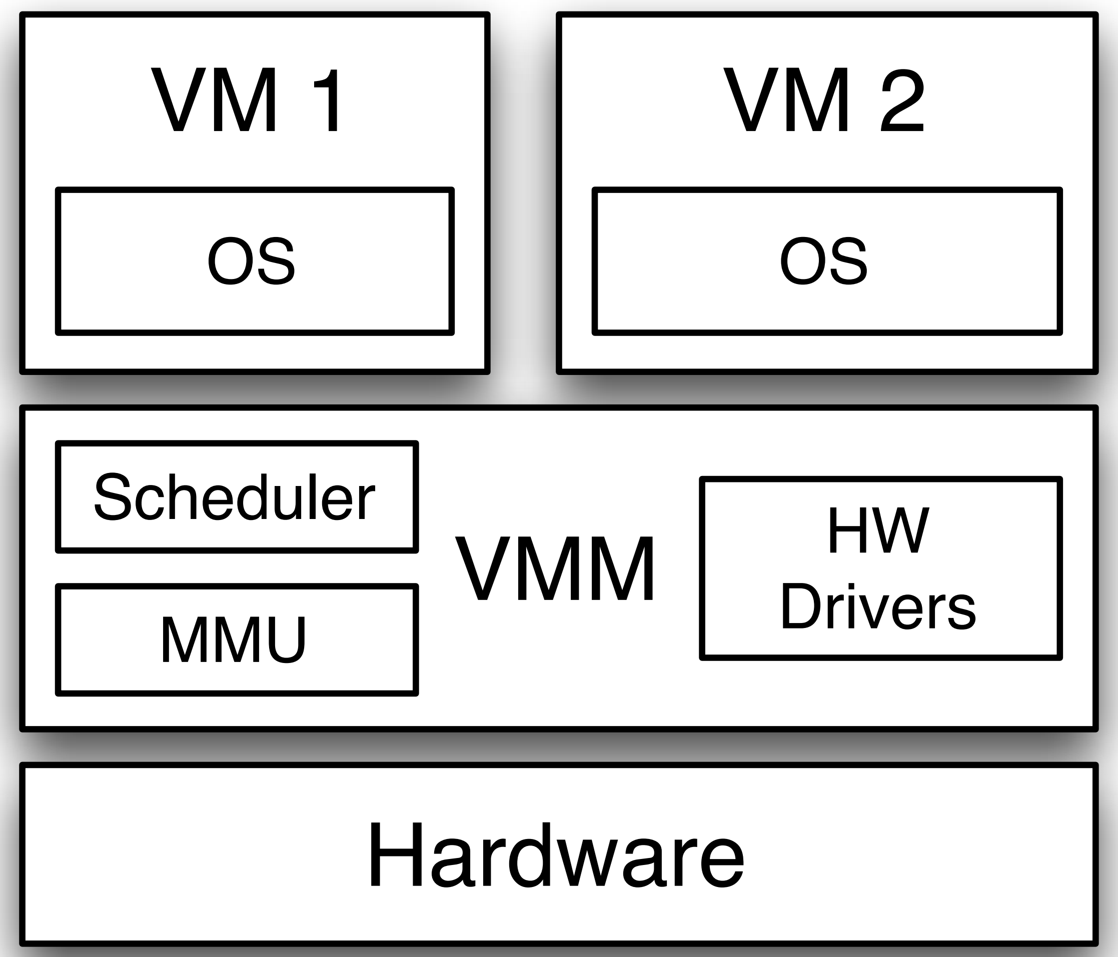
- Development and testing environments
  - A VM with standard tools is distributed amongst developers
  - Releasing new revisions of tools, patches, etc. is very simple
- Business Agility and Productivity
  - It allows to easily transform environments (Development to test, back to development, etc)
- Deployment of Patches in controlled environments
- Allows for testing in production hardware before official activation



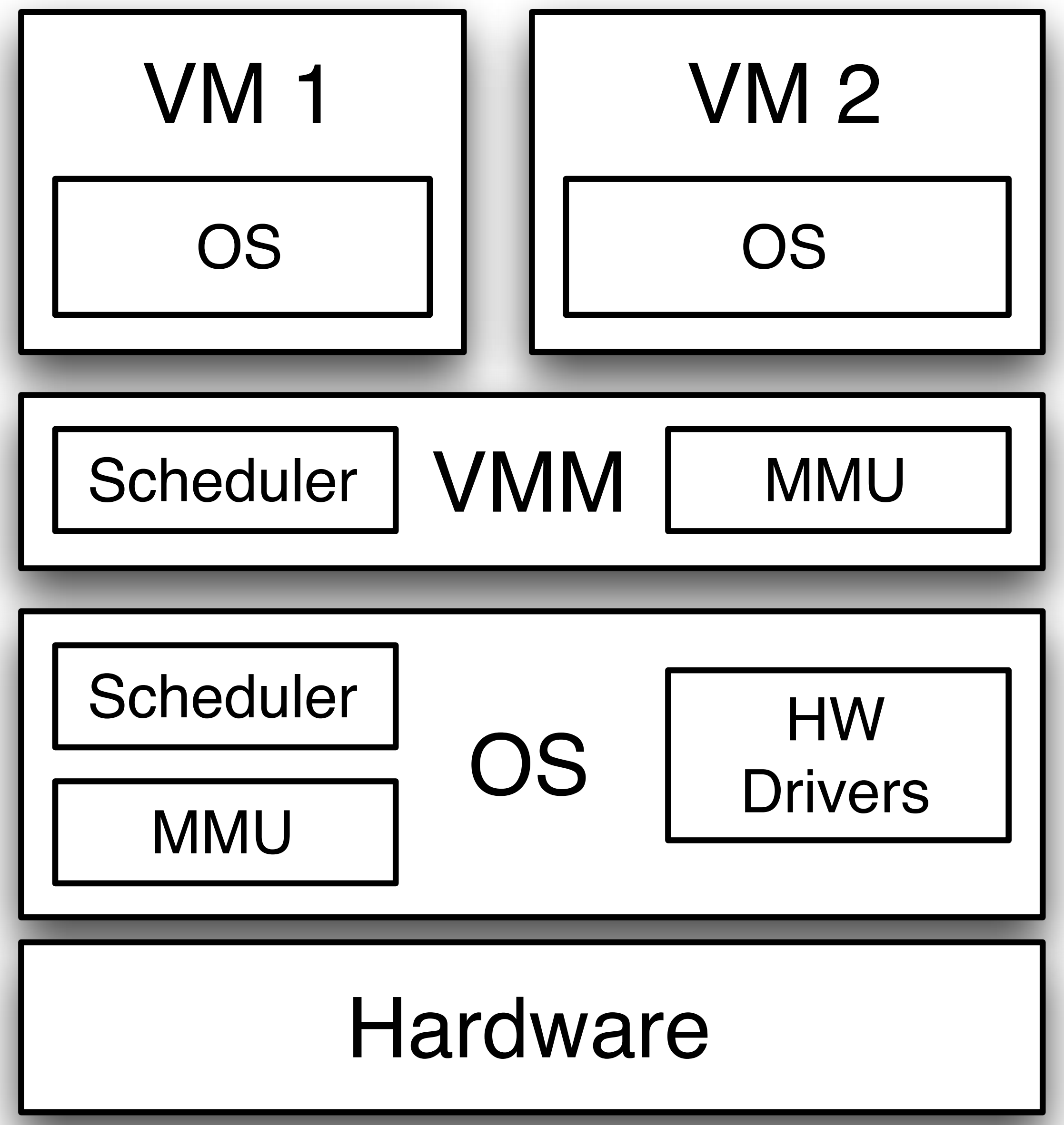
VM Taxonomy


Process VMs
System VMs
Same ISA
Different ISA
Same ISA
Different ISA
Multiprogrammed Systems
Dynamic Translators
Classic-System VMs
Whole-System VMs
Dynamic Binary Optimizers
HLL VMs
Hosted VMs
Codesigned VMs

System Virtualization



Native Virtualization



Hosted Virtualization

Virtualization Implementations

- ***Full Virtualization***
  - Software Based
  - VMware and Microsoft
- ***Para Virtualization***
  - Cooperative virtualization
  - Modified guest OS
  - VMware, Xen
- ***Hardware-assisted Virtualization***
  - Unmodified guest OS
  - VMware and Xen on virtualization-aware hardware platforms

Resource Control

- VMM must maintain *overall control* of the hardware resources
  - Hardware resources are assigned to VMs when they are created/ executed
  - Should have a way to get them back when they need to assigned to a different VM
  - Similar to multi-programming in OS
- Privileged Resources
  - Certain resources are accessible only to and managed by VMM
  - Interrupts relating to such resources must then be handled by VMM
  - Privileged resources are emulated by VMM for the VM
- All resource that could help maintain control are marked privileged
  - "Interval timer" is used to decide VM scheduling
  - "Page table base register" (CR3 on x86) is used to isolate VM memory

Classes of instructions

- PRIVILEGED instructions trap if executed in user mode and do not trap if executed in kernel mode
- SENSITIVE instructions interact with hardware
  - CONTROL-sensitive instructions attempt to change the configuration of resources in the system
  - BEHAVIOR-sensitive instructions have their result depending on the configuration of resources (e.g. mode of operation)
- INNOCUOUS instructions are not sensitive

Popek & Goldberg Theorem (1974)

For any conventional third-generation computer a virtual machine monitor with the following properties:

1. Efficiency: innocuous instruction must be executed natively

2. Resource Control: guest can not directly change host resources

3. Equivalence: app behavior in guest must be identical to app behavior in host

may be constructed if the set of sensitive instructions for that computer is a subset of the set of privileged instructions

Full Virtualization

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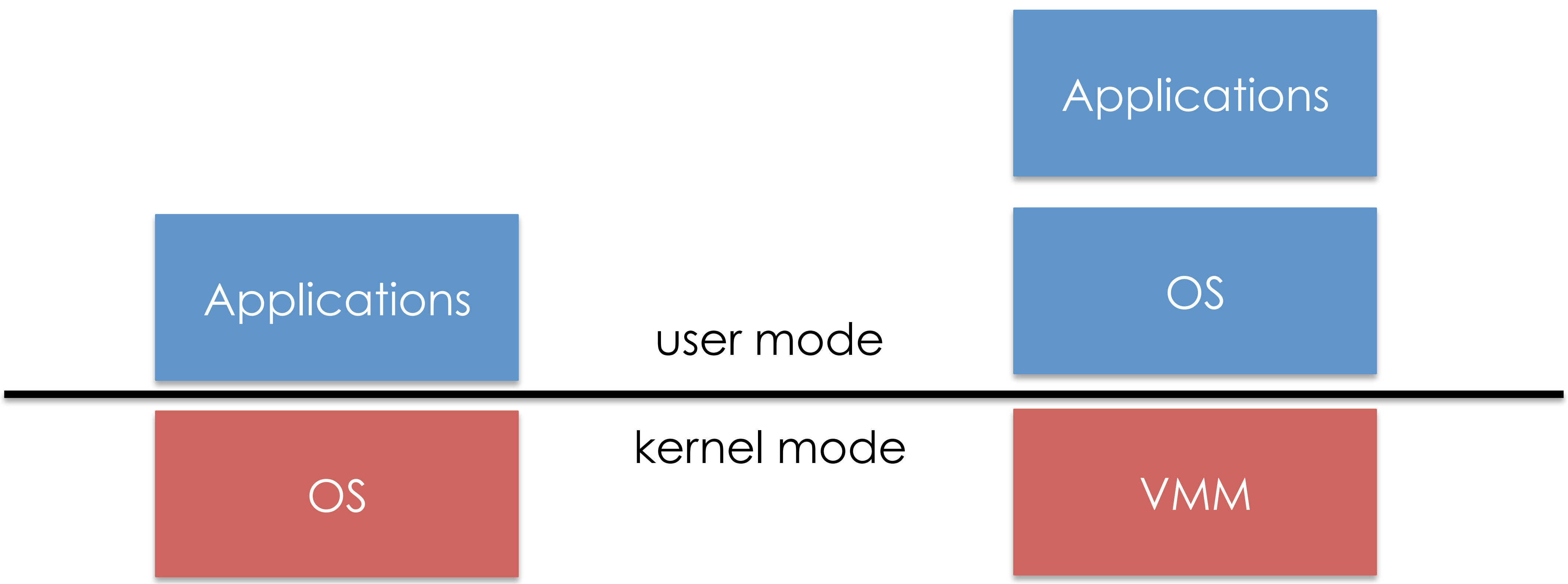
Trap & Emulate

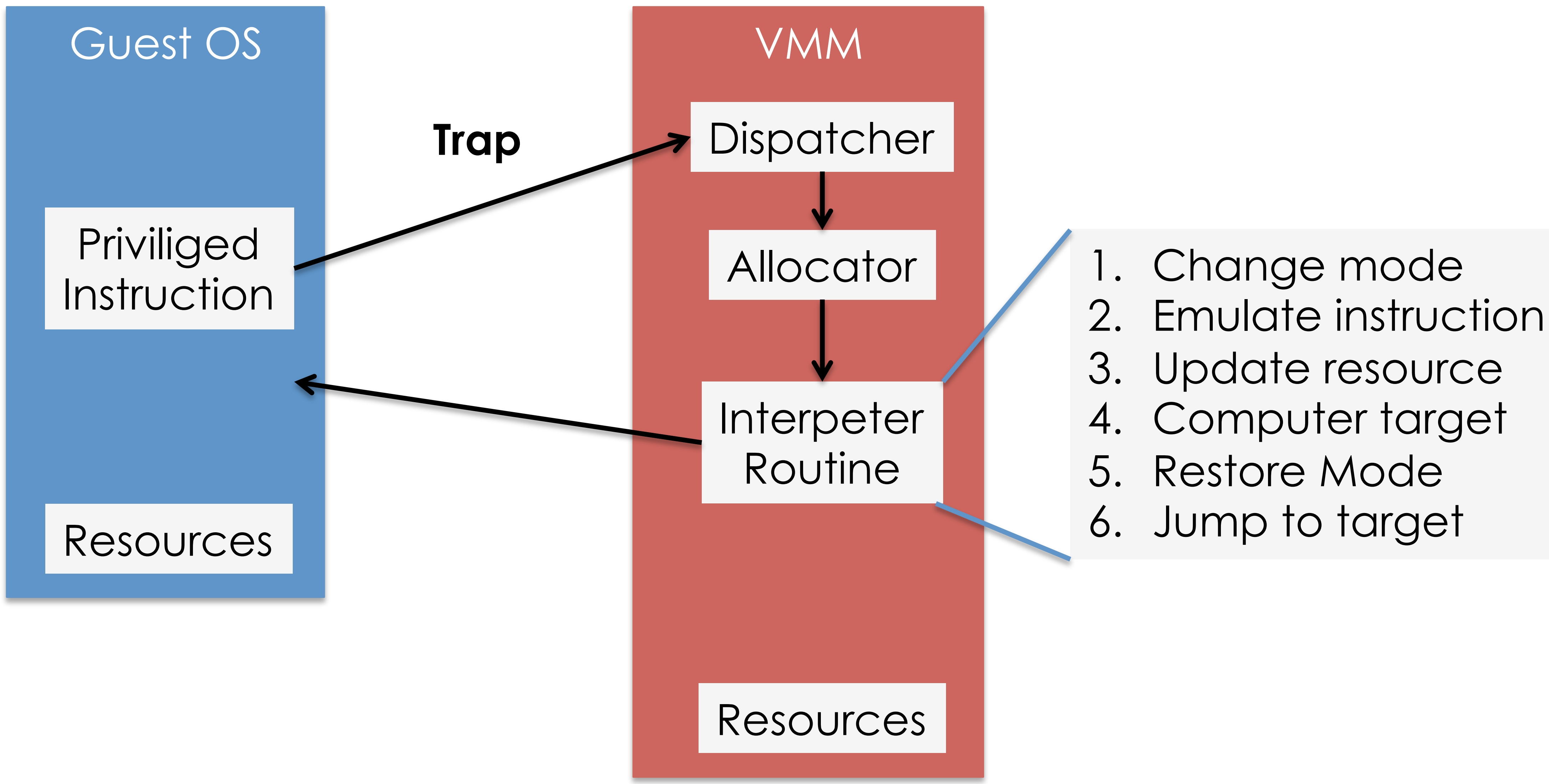
- Must be able to "detect" when VMM must intervene
- Some ISA instructions must be "trapped" and "emulated"
- Must De-Privilege OS
- Very similar to the way programs transfer control to the OS kernel during a system call



Privileged Resources

- Each VM's privileged state differs from that of the underlying HW.
- Guest-level **primary structures** reflect the state that a guest sees.
- VMM-level **shadow structures** are copies of primary structures.
- Traps occur when **on-chip privileged state** is accessed/modified.
- HW page protection schemes are employed to "detect" when **off-chip privileged** state is accessed/modified

Handling of Privileged Instructions

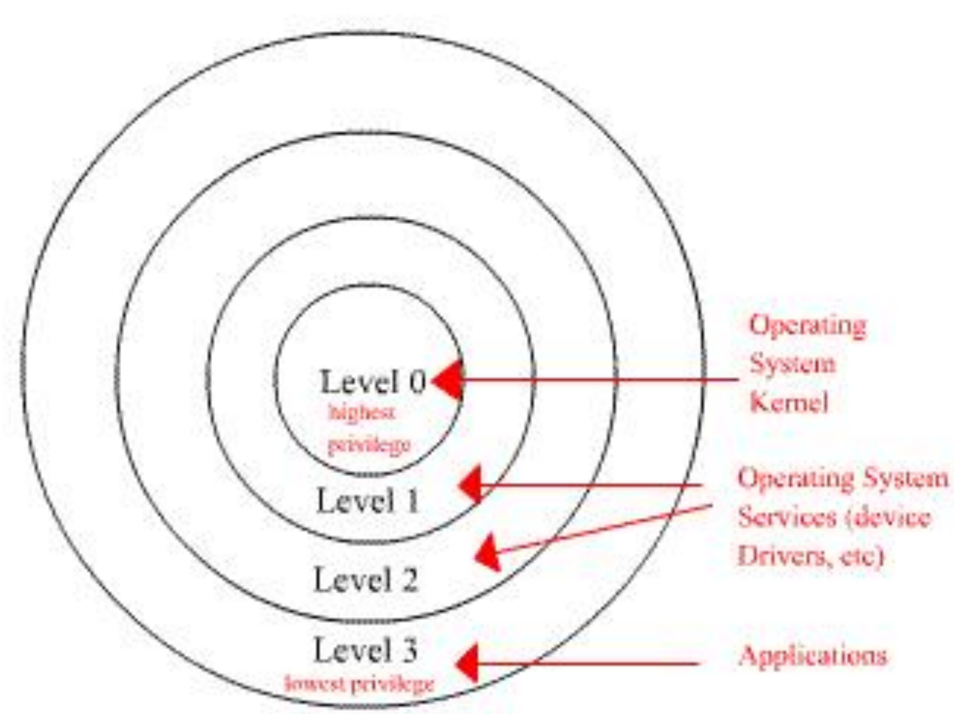


Traps are expensive!

Is X86 (fully) virtualizable?

- Lack of trap when priviliged instructions run at user level
- Some privileged instructions execute only in ring 0 but do not fault when executed outside ring 0
- Masking interrupts can only be done in ring 0

Intel IA32 Protection Rings



Example: POPF

- Same instruction **behaves differently** depending on execution mode
- **User Mode**: changes ALU flags
- **Kernel Mode**: changes ALU and system flags
- Does not generate a trap in user mode

The IA-32 instruction set contains 17 sensitive, unprivileged instructions

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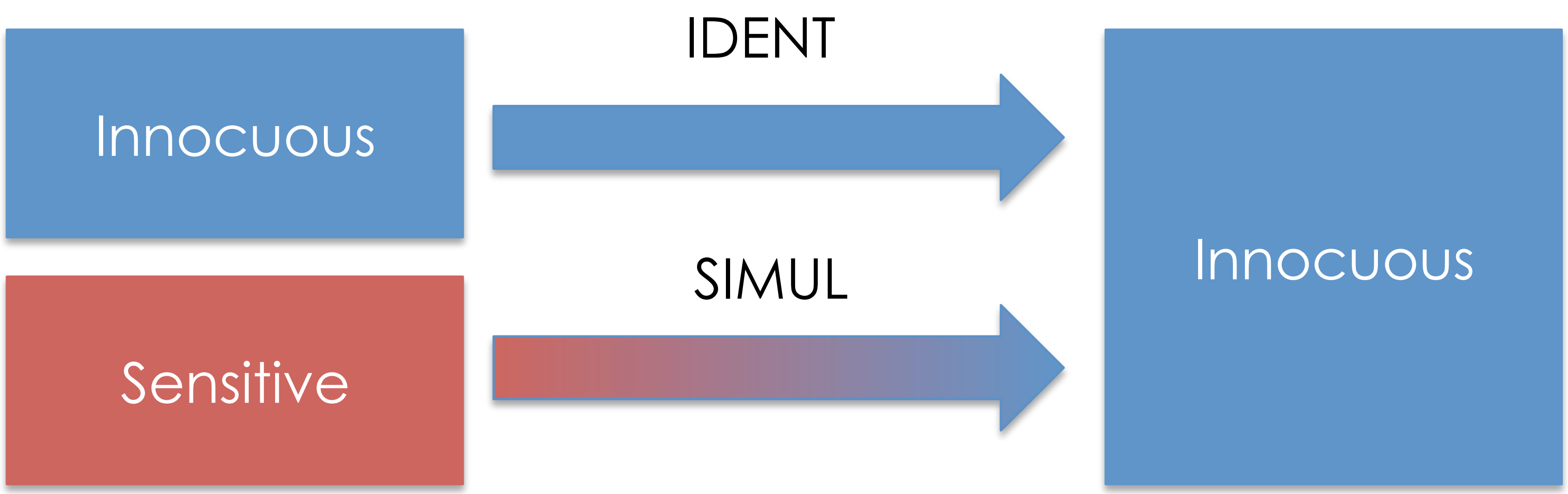
Binay Translation



- **Binary** – input is machine-level code
- **Dynamic** – occurs at runtime
- **On demand** – code translated when needed for execution
- **System level** – makes no assumption about guest code
- **Subsetting** – translates from full instruction set to safe subset
- **Adaptive** – adjust code based on guest behavior to achieve efficiency

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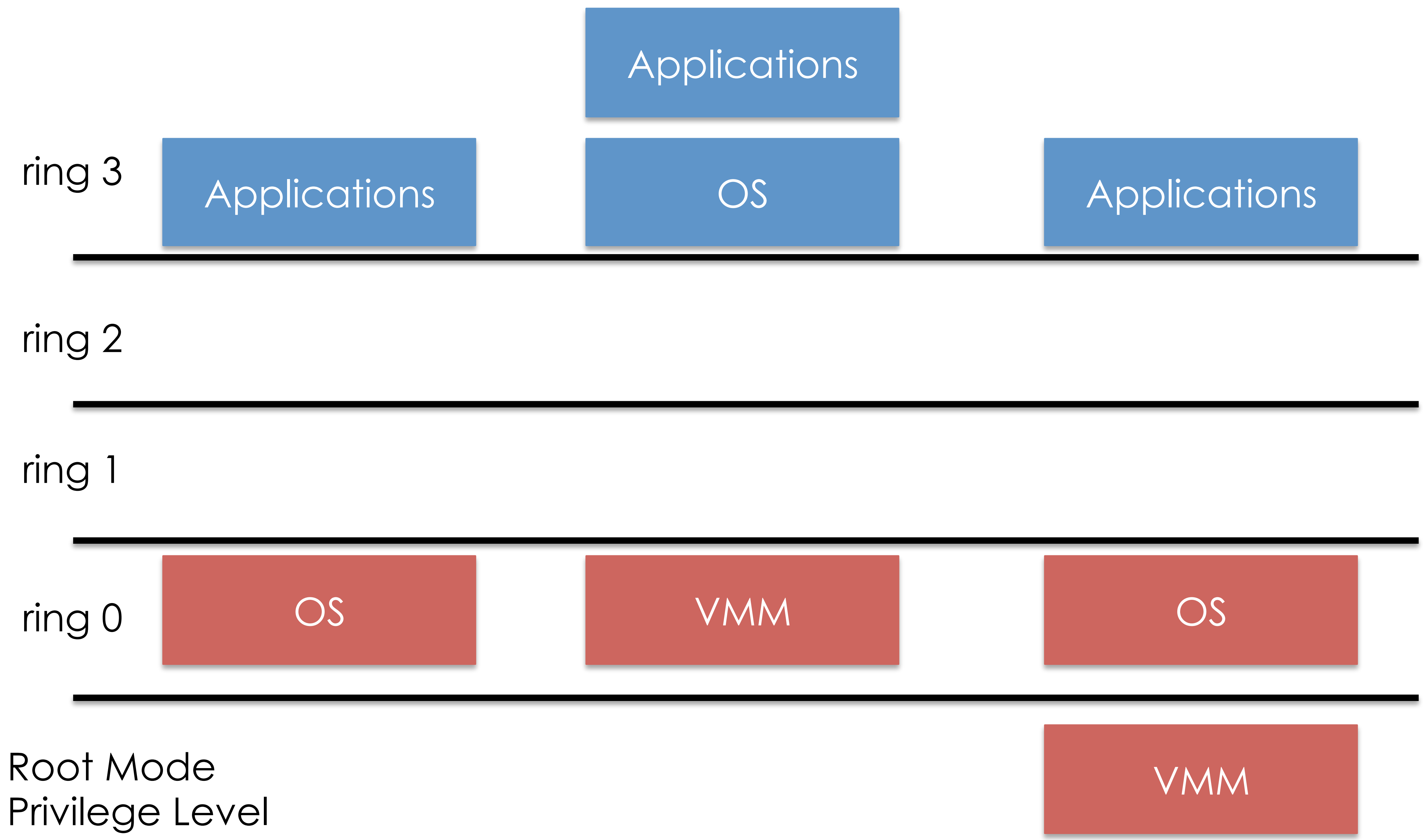
Hardware-assisted Virtualization



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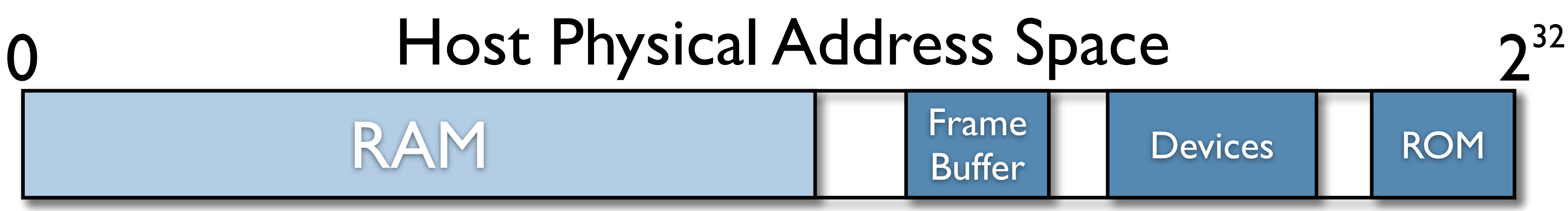
New Hardware Features

- Virtual Machine Control Blocks (VMCBs)
- Root mode privilege level
- Ability to transfer control to/from guest mode.
  - *vmrun* - host to guest.
  - *exit* - guest to host.
- VMM executes *vmrun* to start a guest.
  - Guest state is loaded into HW from in-memory VMCB.
  - Guest mode is resumed and guest continues execution.
- Guests execute until they “toy” with control bits of the VMCB.
  - An *exit* operation occurs.
  - Guest saves data to VMCB.
  - VMM state is loaded into HW - switches to host mode.
  - VMM begins executing.

Virtualizing Virtual Memory



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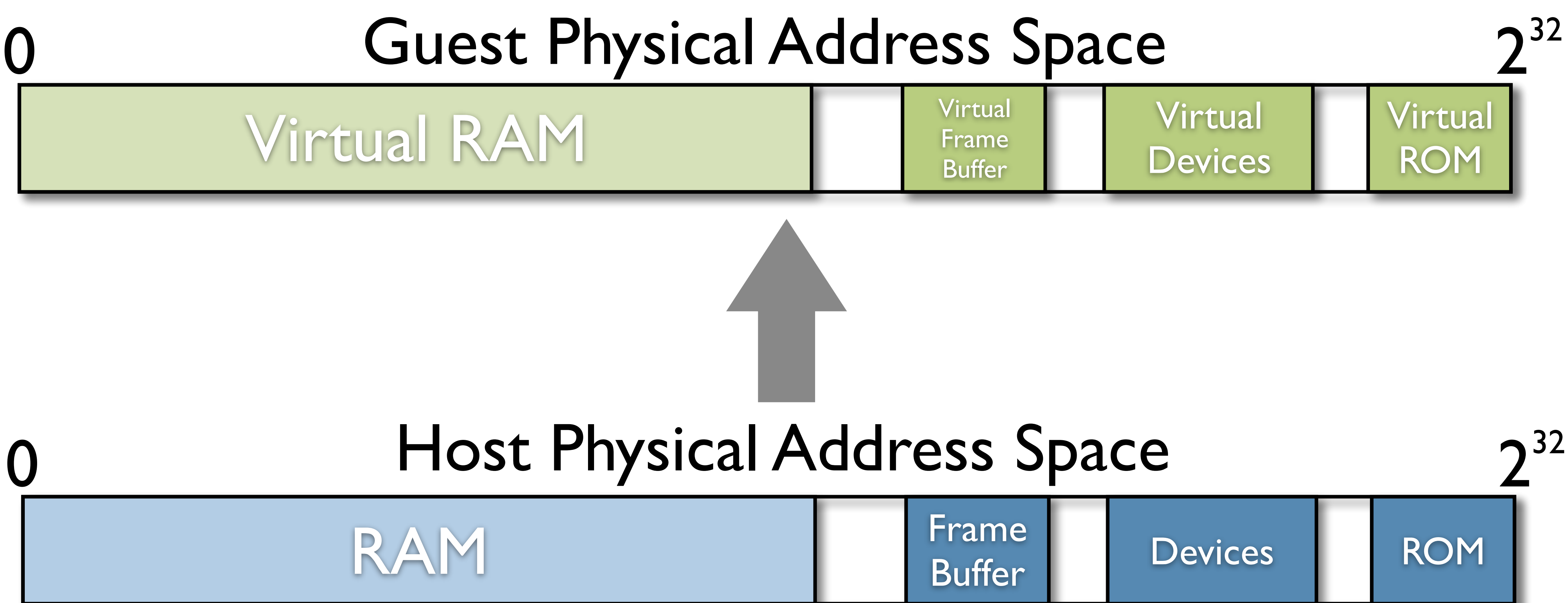

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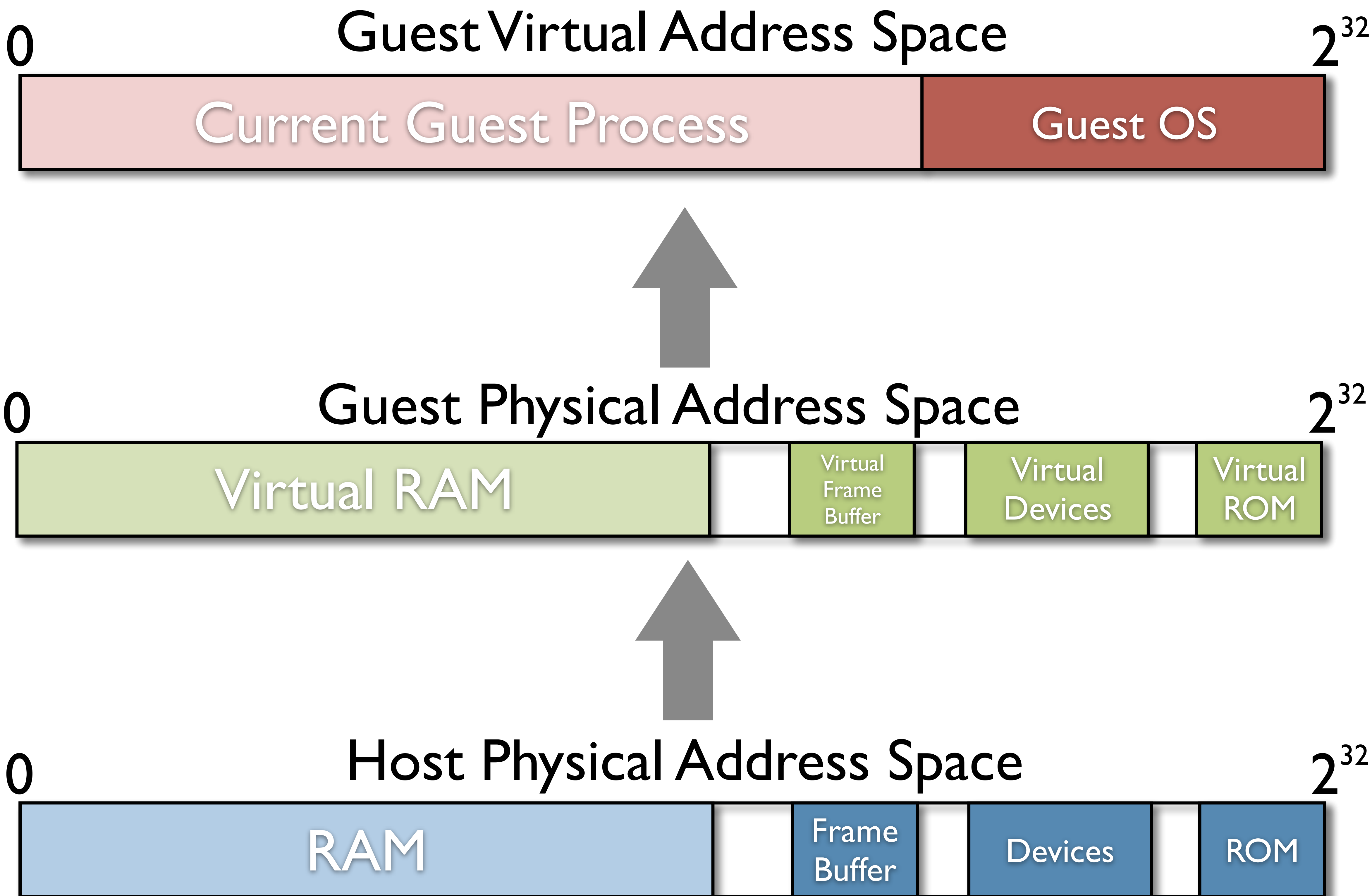

Shadow Page Table

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- The VMM maintains a mapping from each guest physical memory page to the host physical memory page
  - PMAP data structure

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- The VMM seems able to intercept MMU hardware requests to translate GVAs
  - Monitoring PTBR
  - Two memory accesses, to guest virtual memory page table and PMAP

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  - Monitoring
  - Two memory accesses, to guest virtual memory page table and PMAP
- So what the hell is a shadow page table?

What about the TLB?

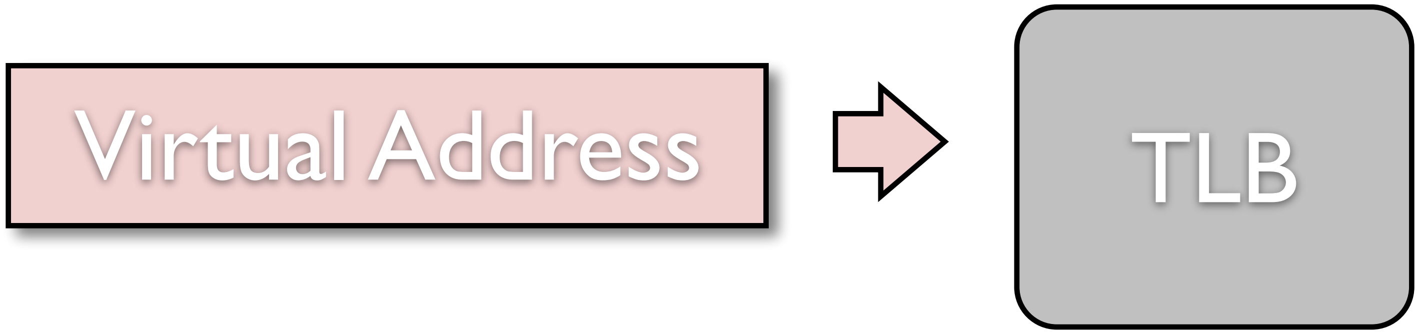
Shadow Page Table

- The VMM must intercept all VM instructions that manipulate:
  - The hardware TLB contents
  - Guest OS page table
- The actual hardware TLB is updated based on the separate shadow page tables
  - They contain the guest virtual to host physical address mapping
- The VMM must protect the host frames containing the guest page tables!

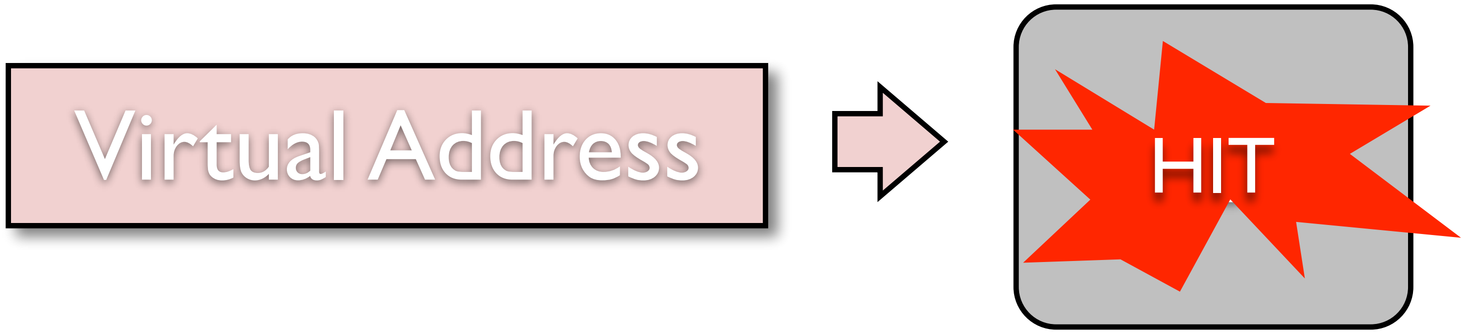
Shadow Page Tables with TLB

Virtual Address

Shadow Page Tables with TLB



Shadow Page Tables with TLB



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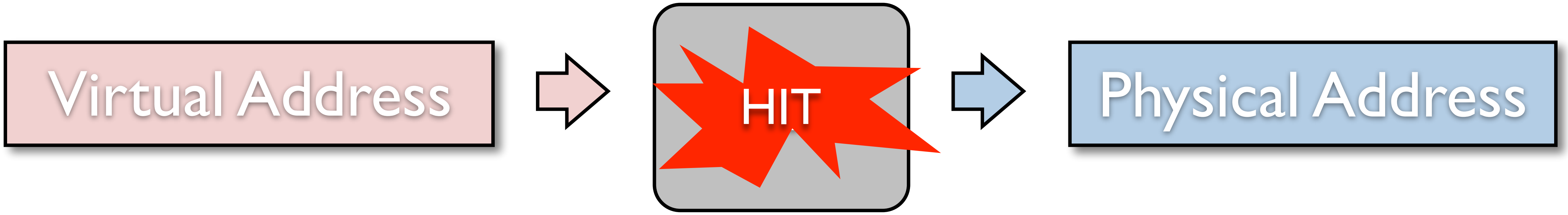

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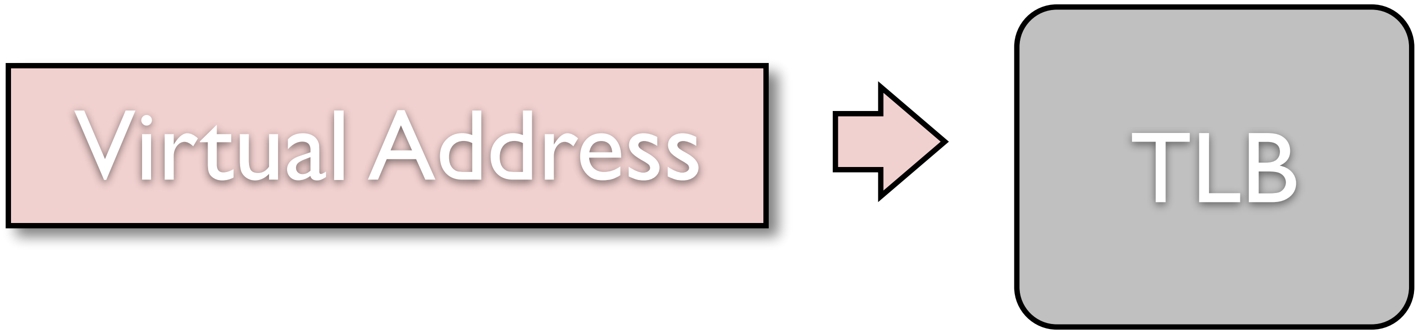

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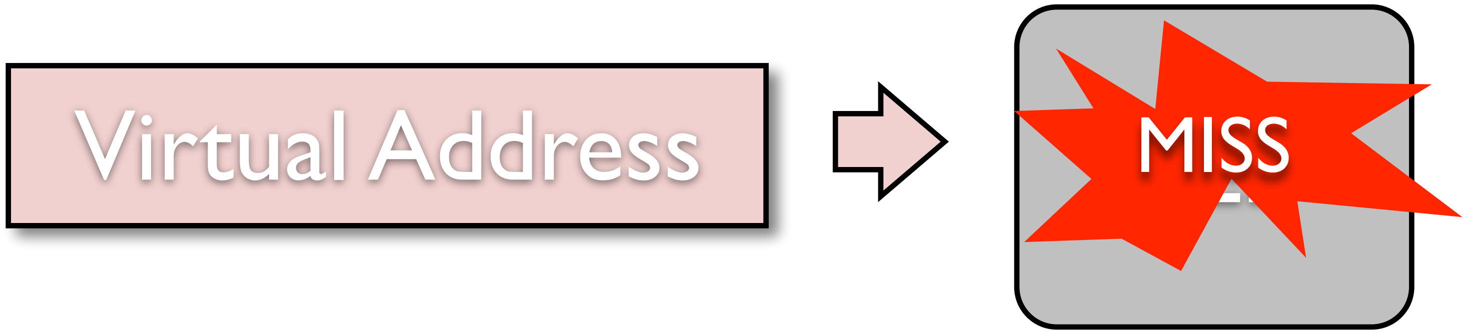

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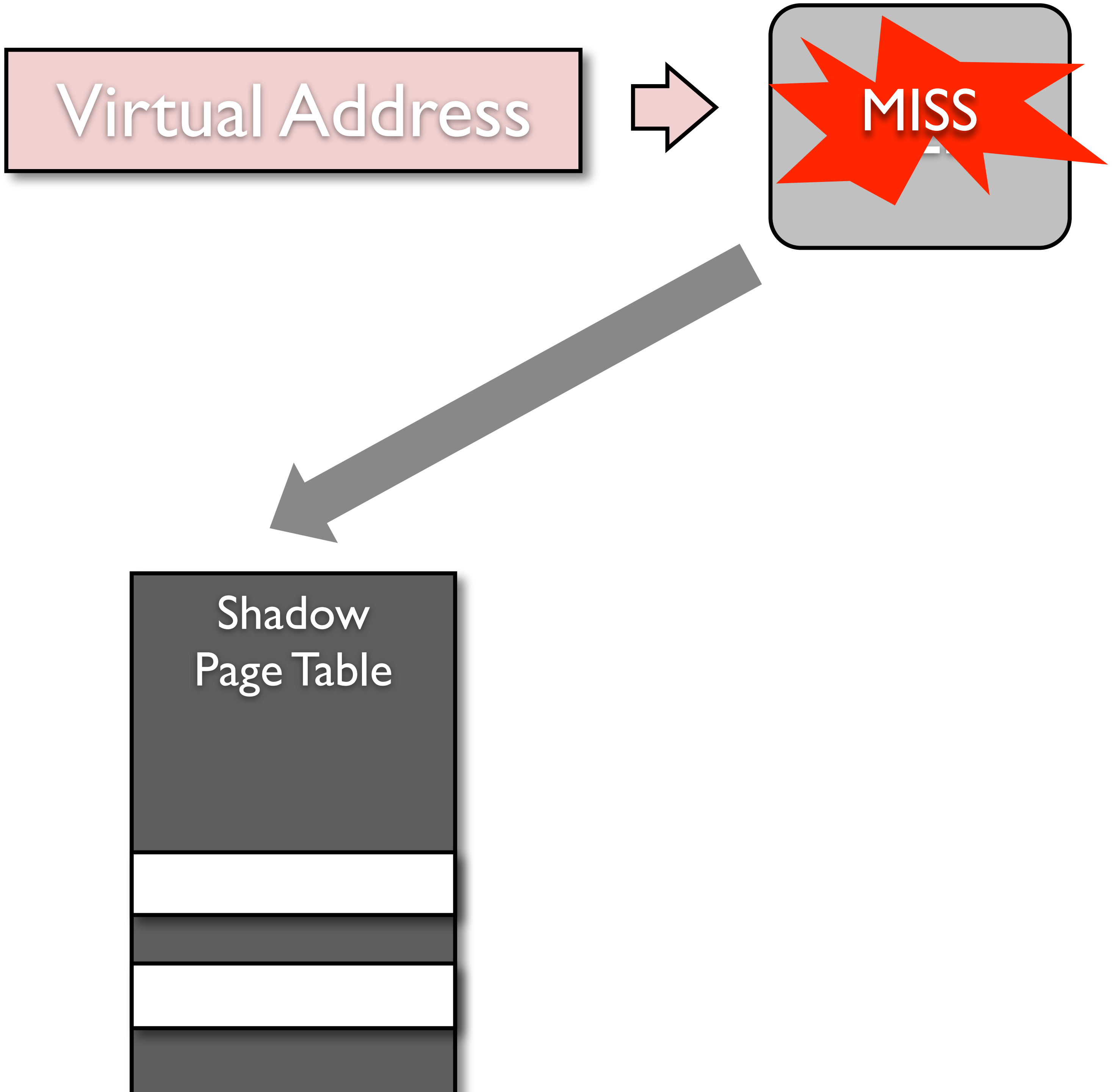

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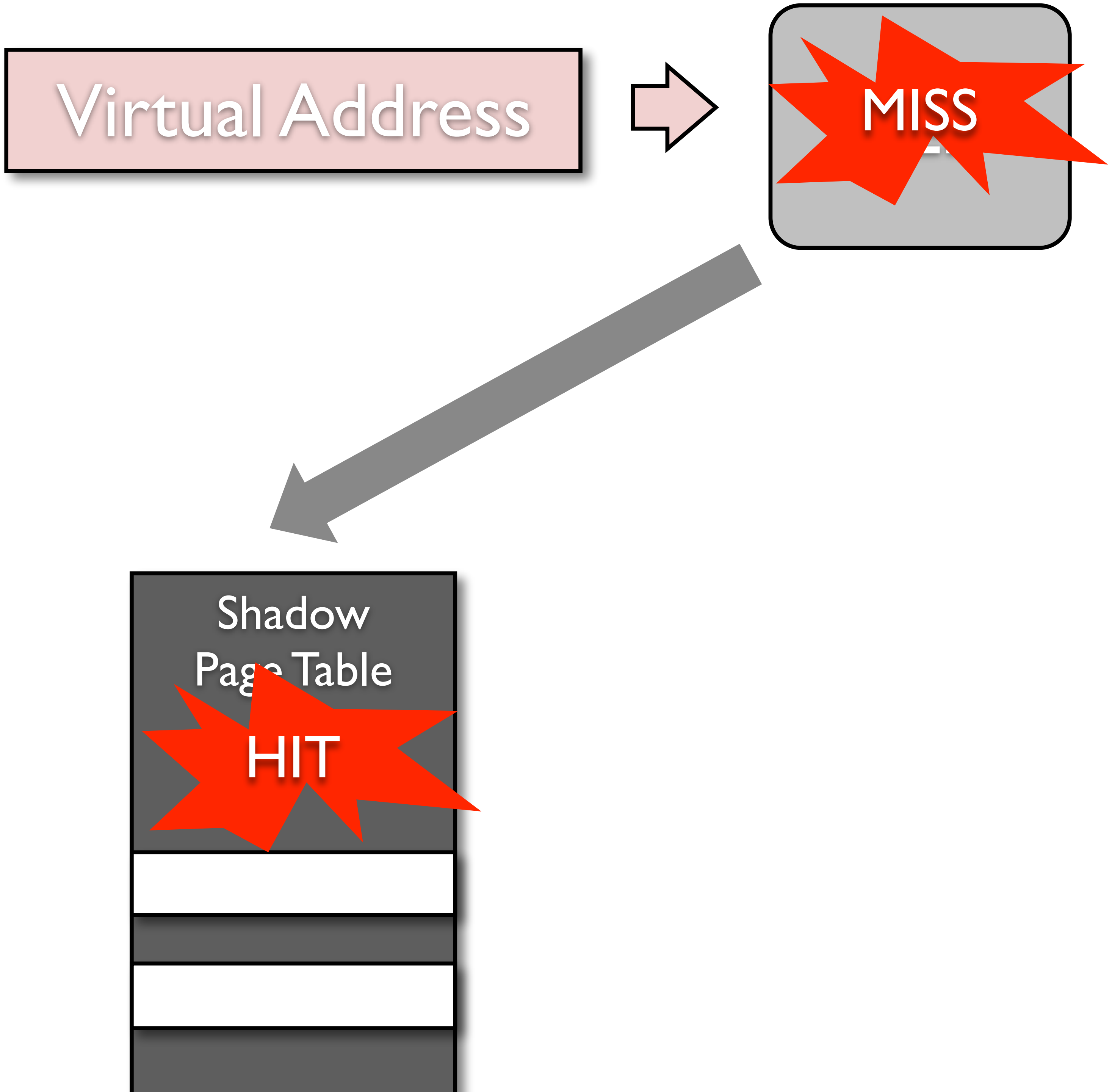

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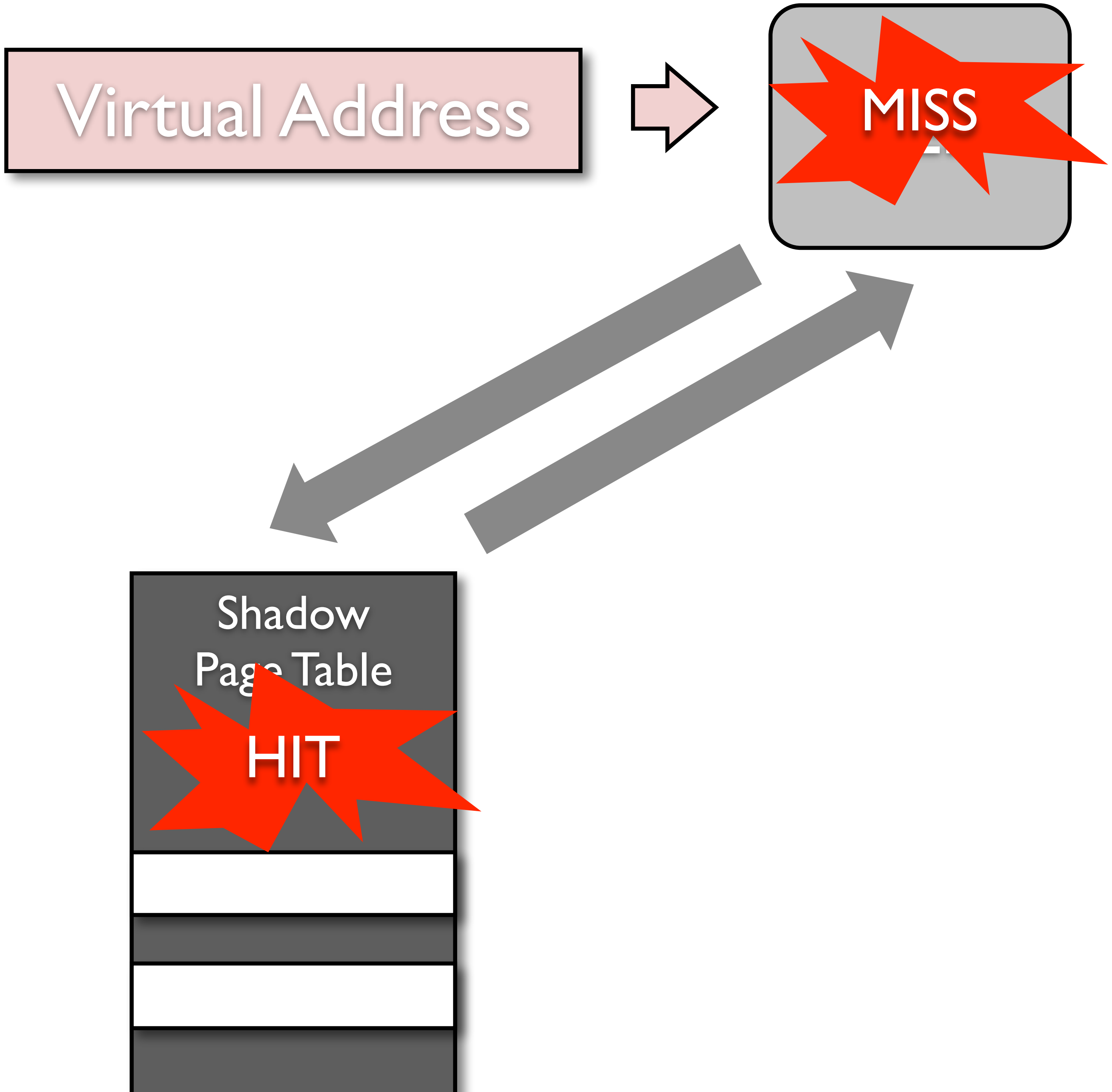

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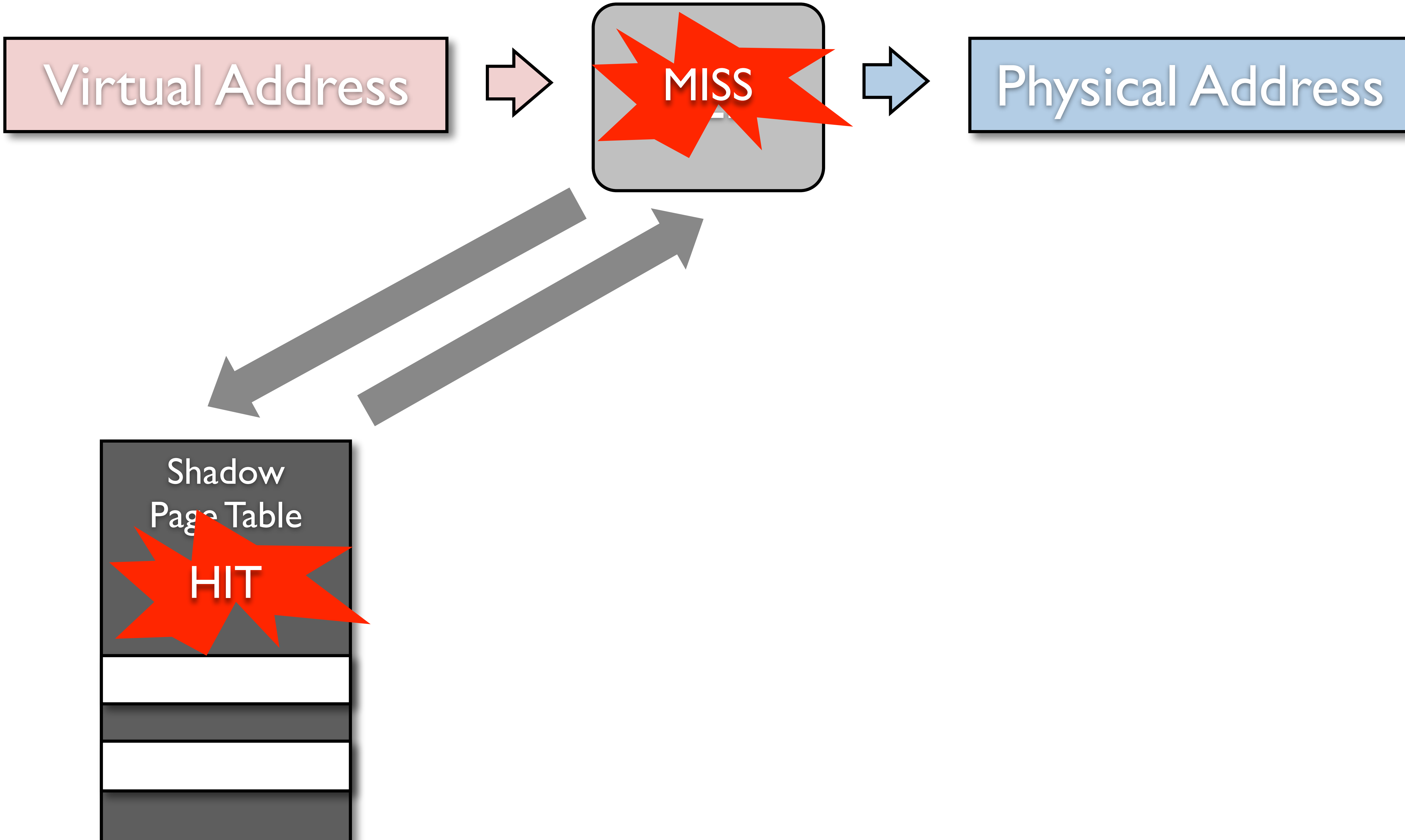

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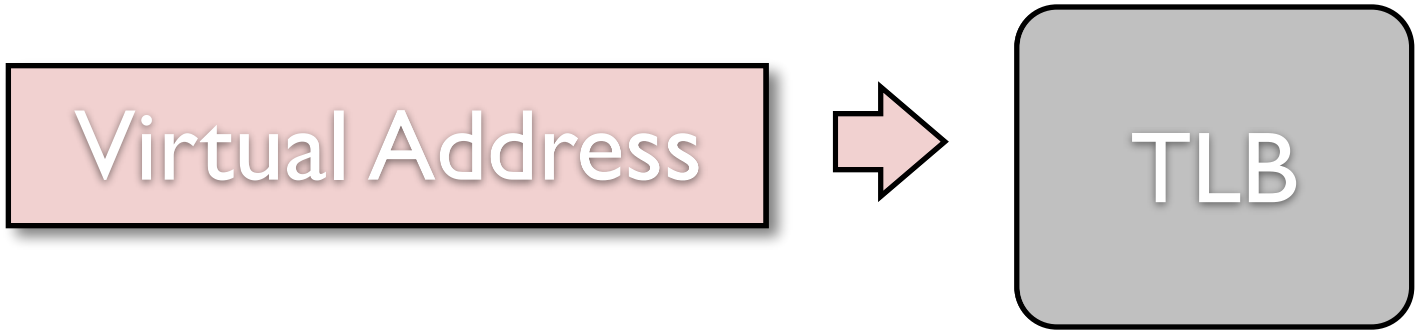

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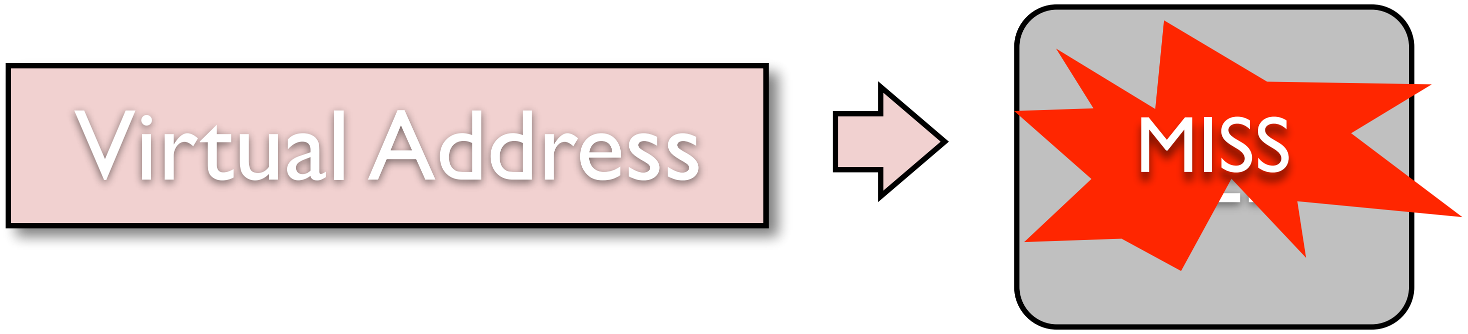

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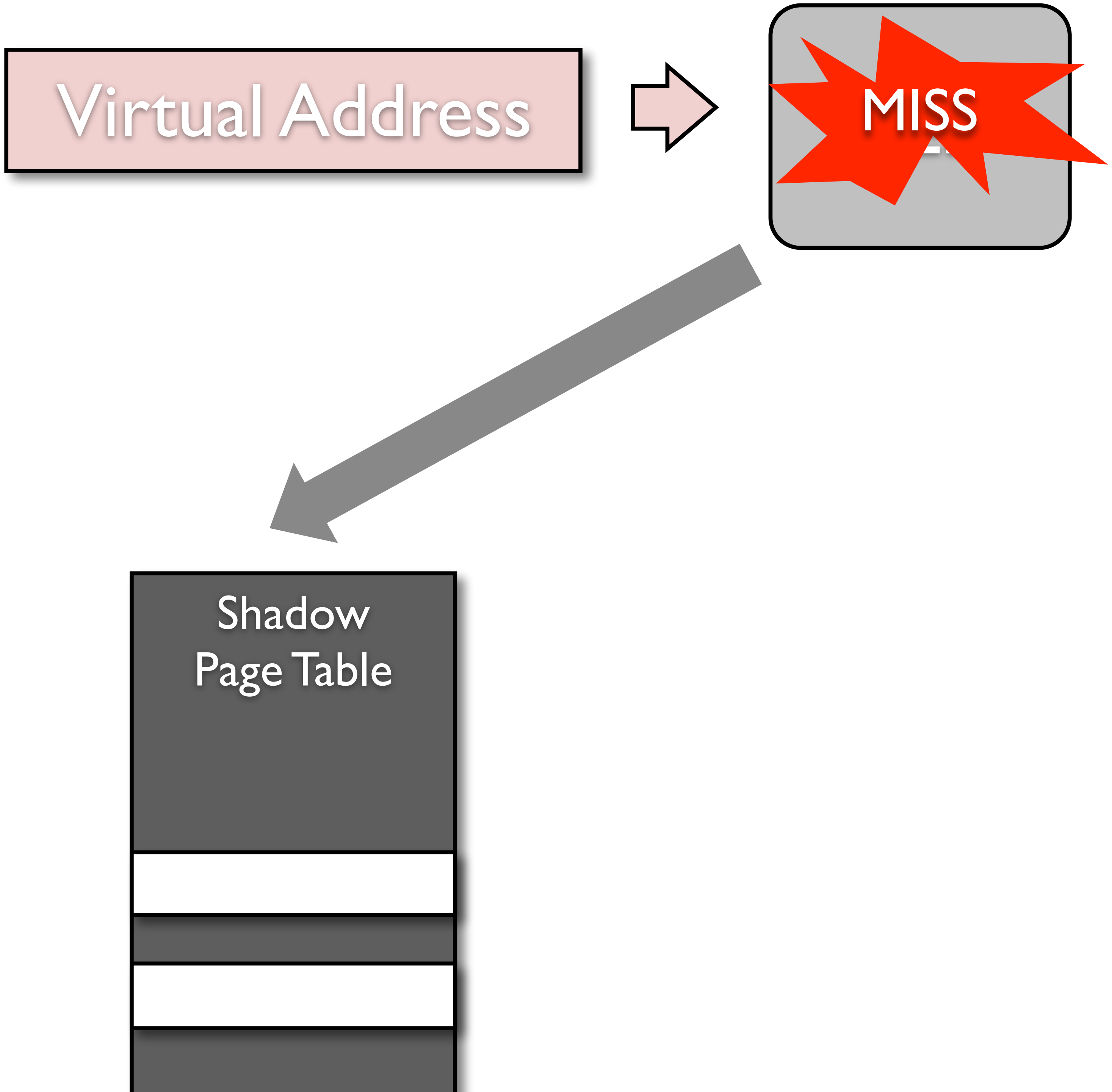

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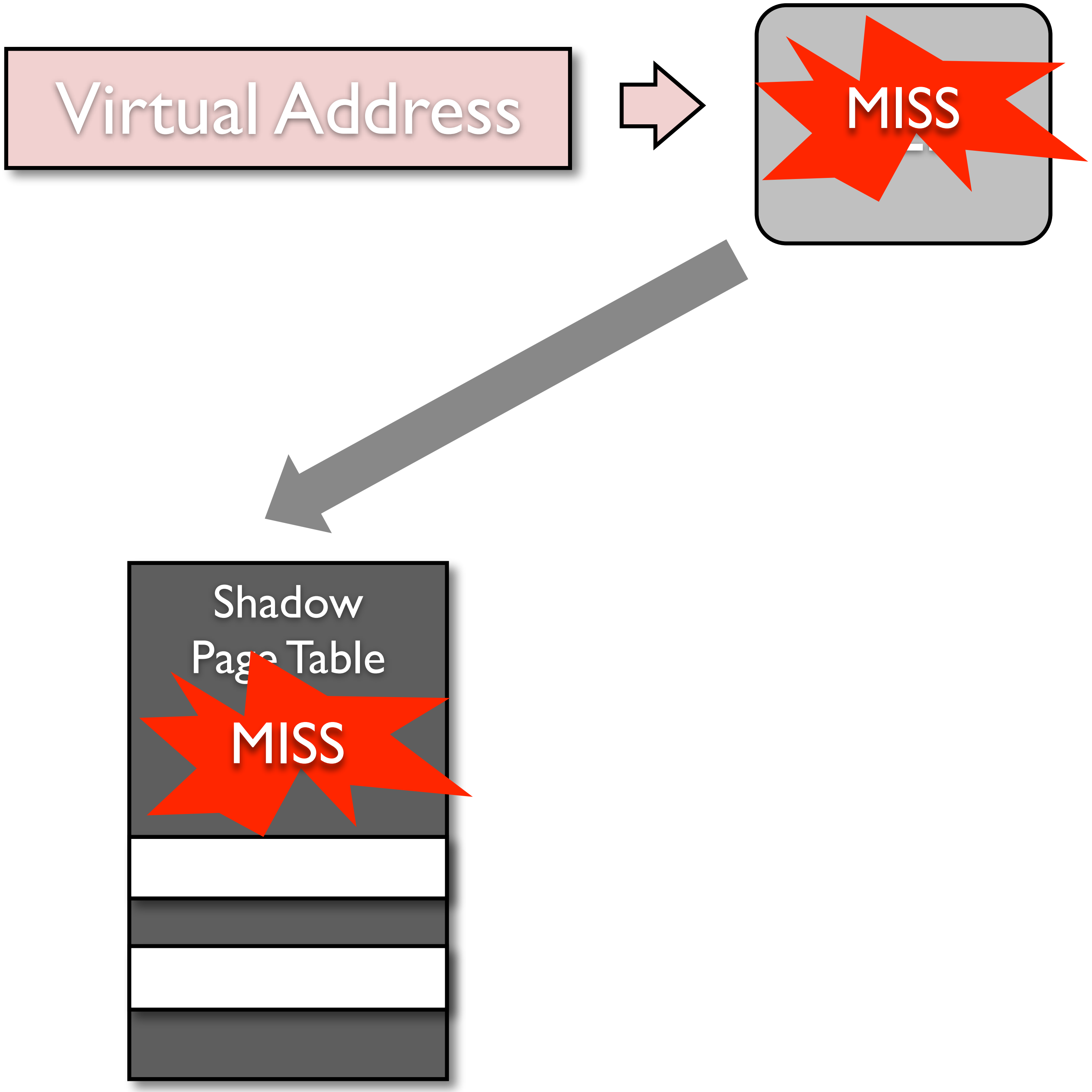
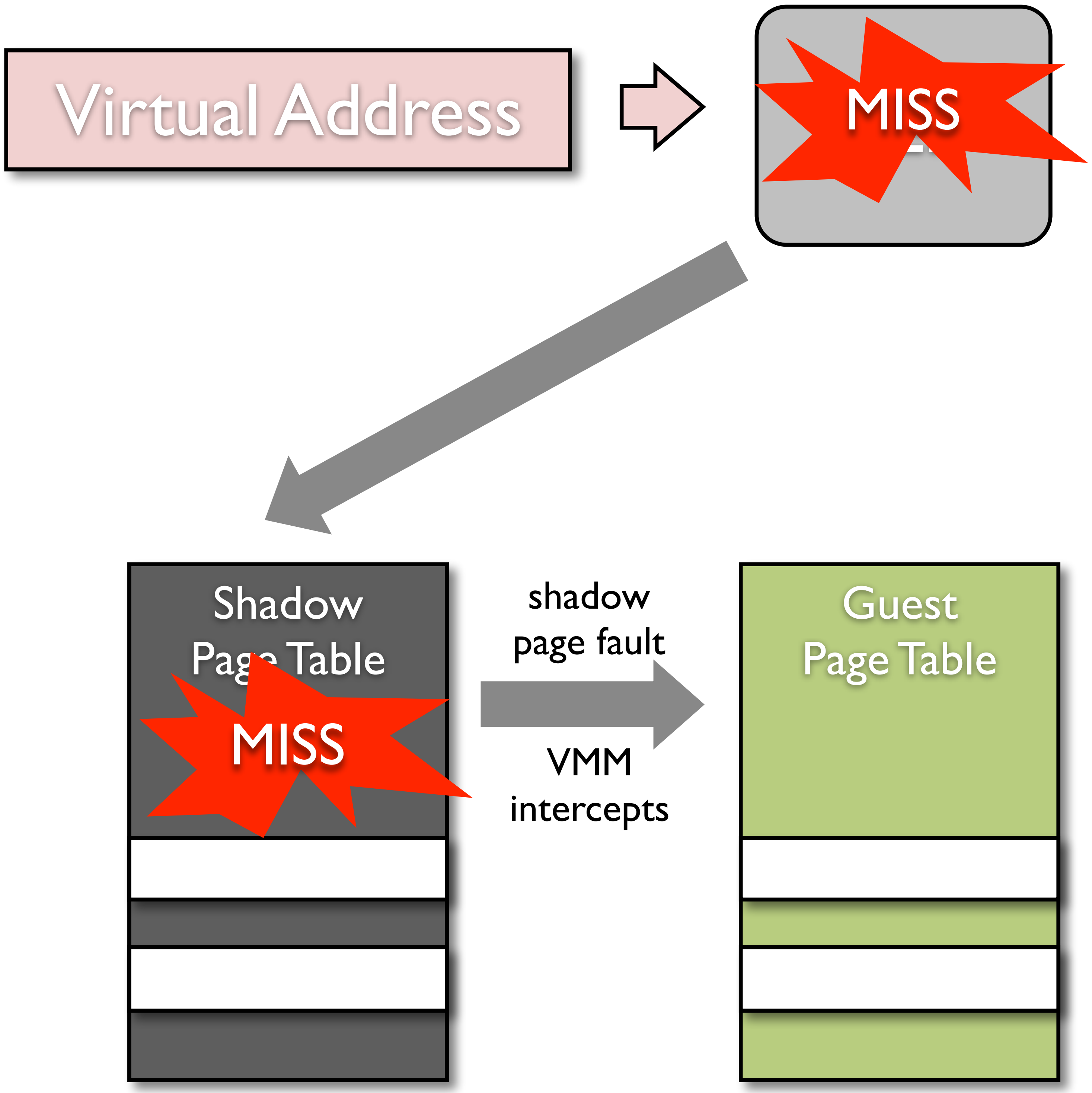


Shadow Page Tables with TLB



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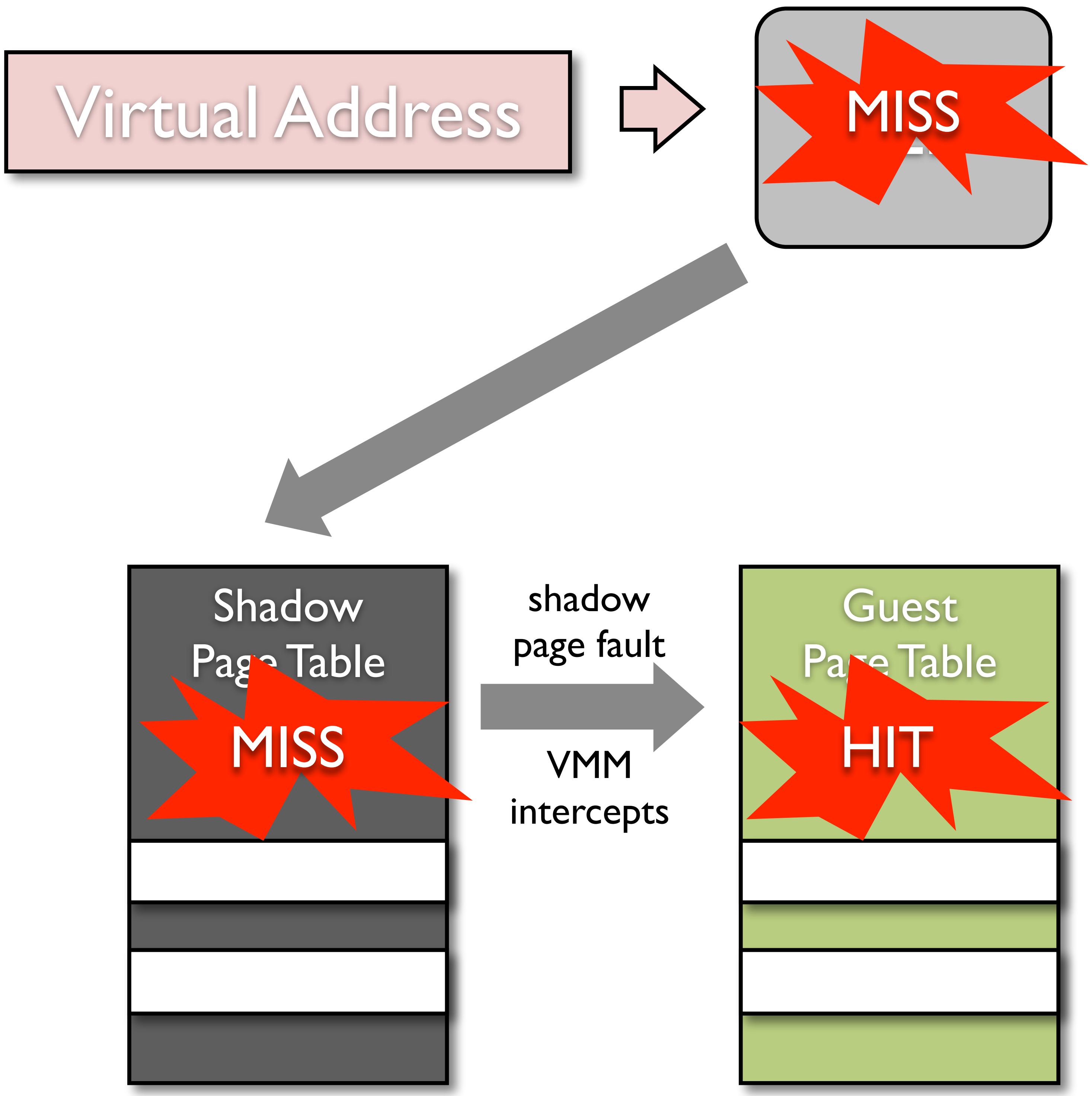

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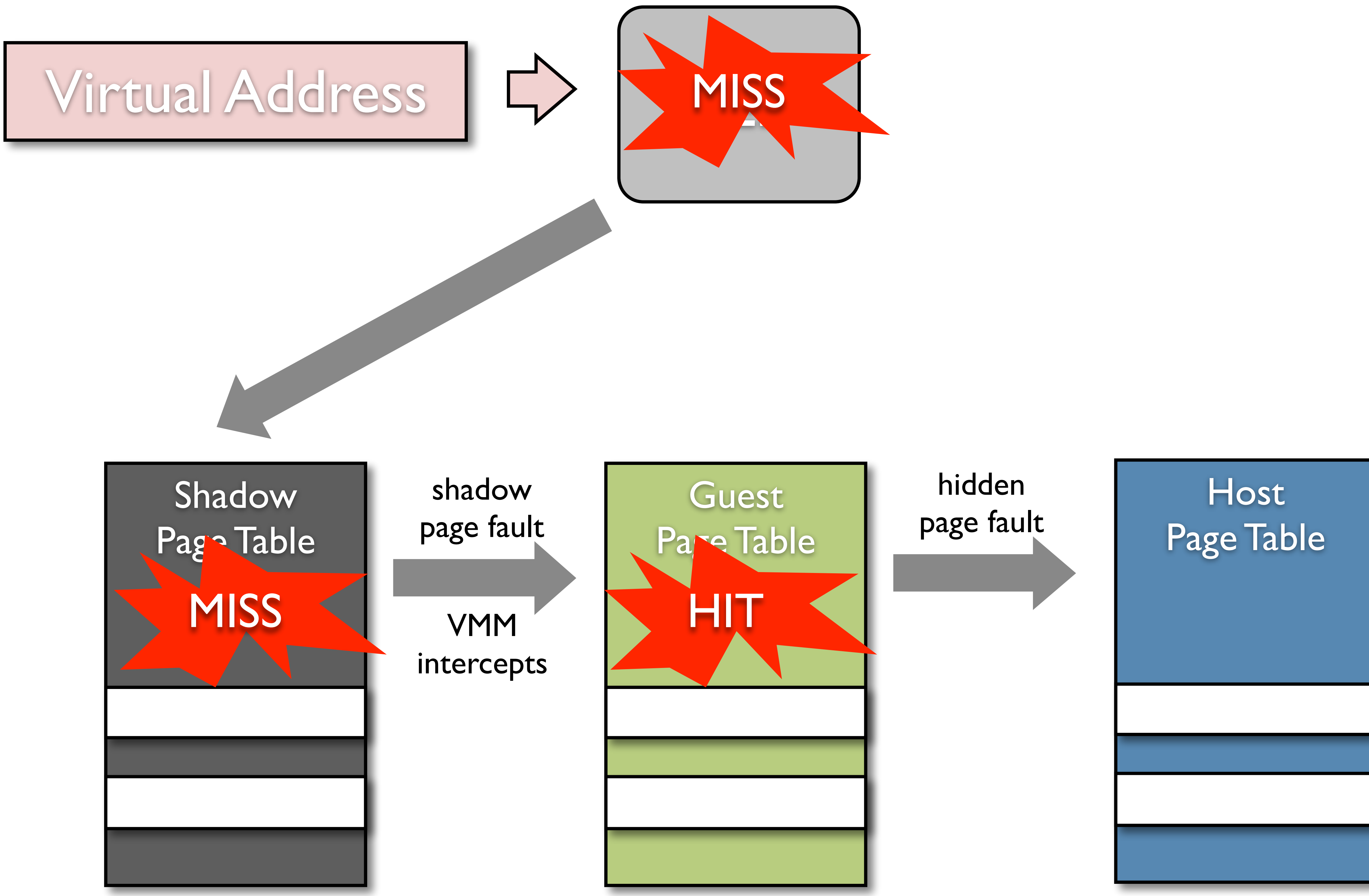

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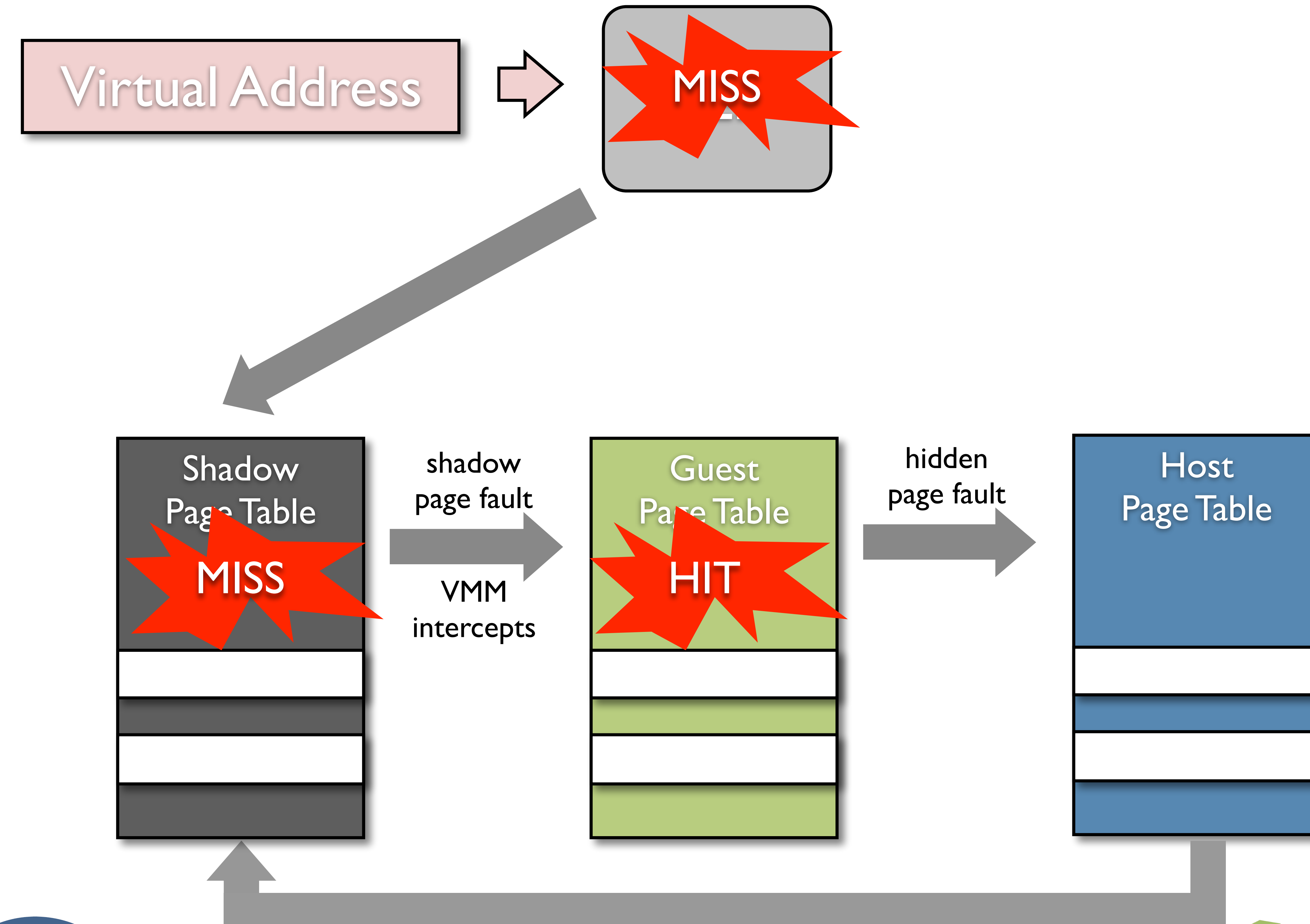

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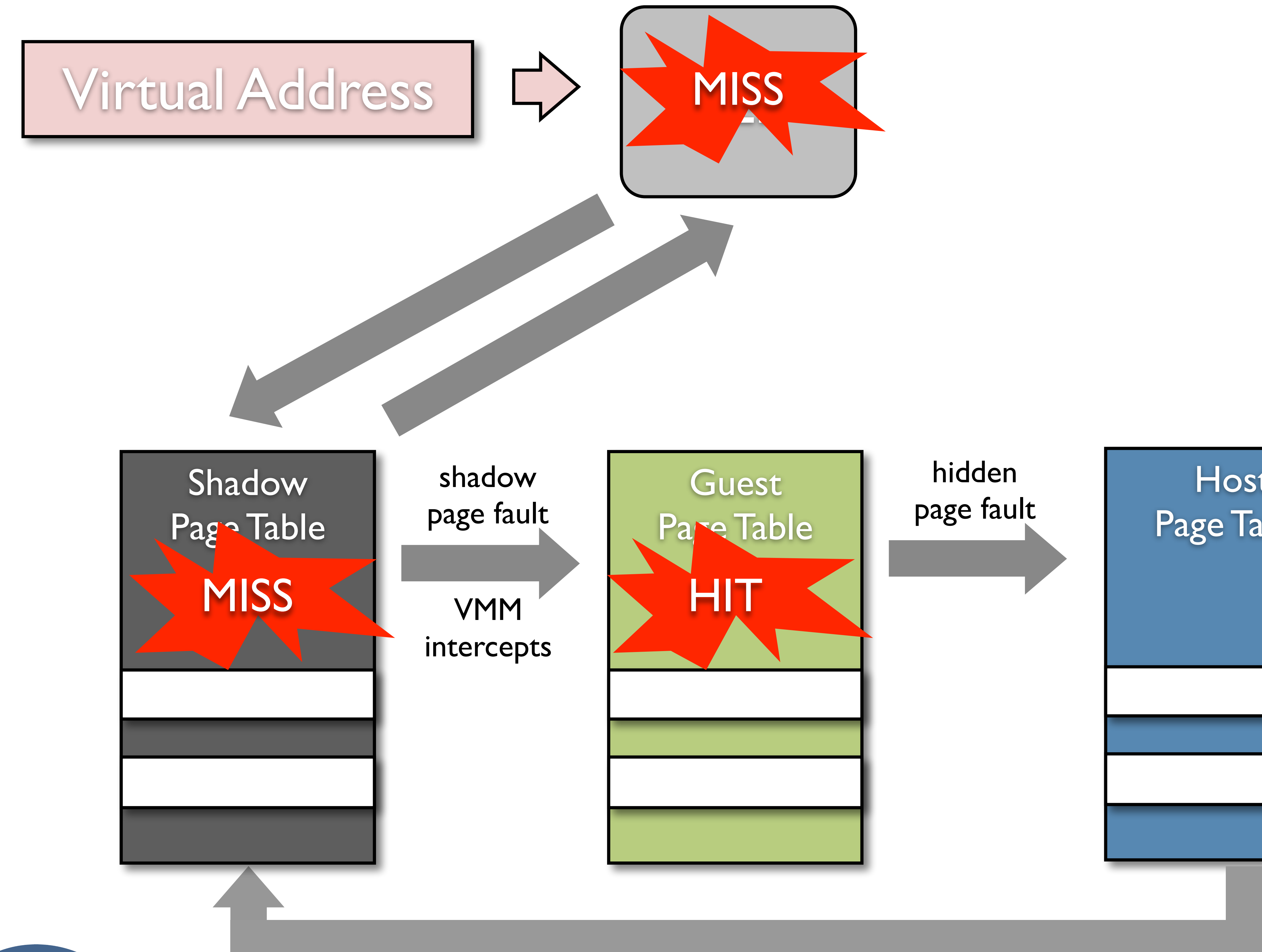

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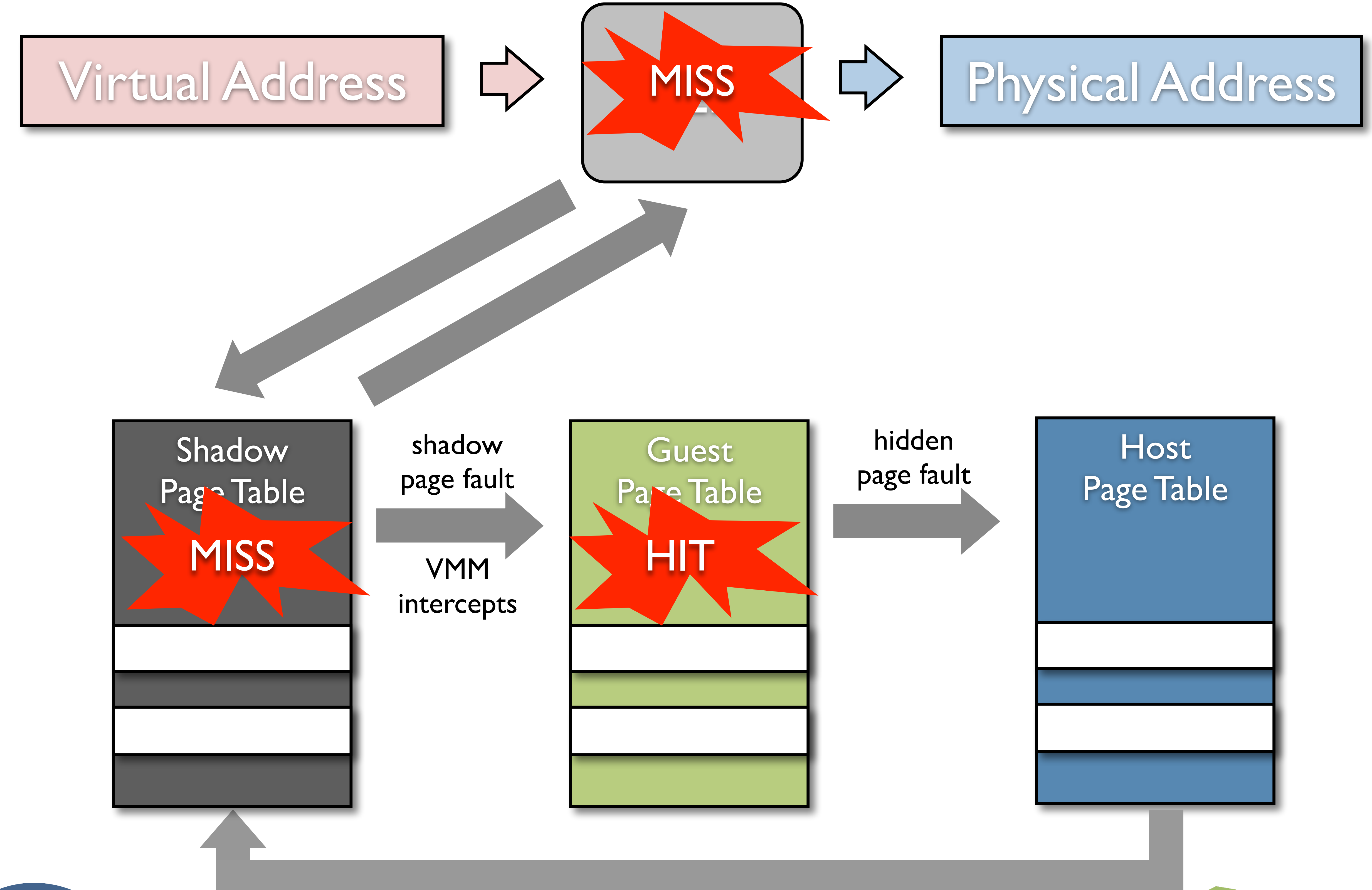

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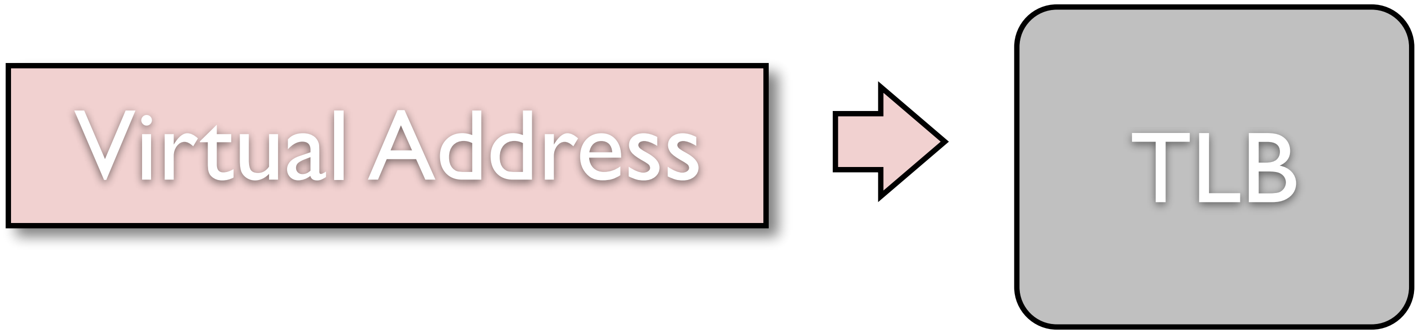

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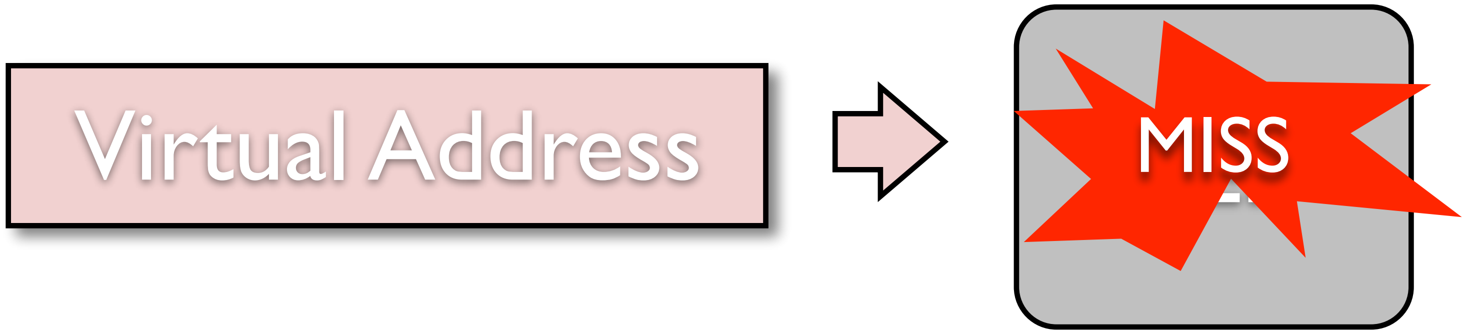

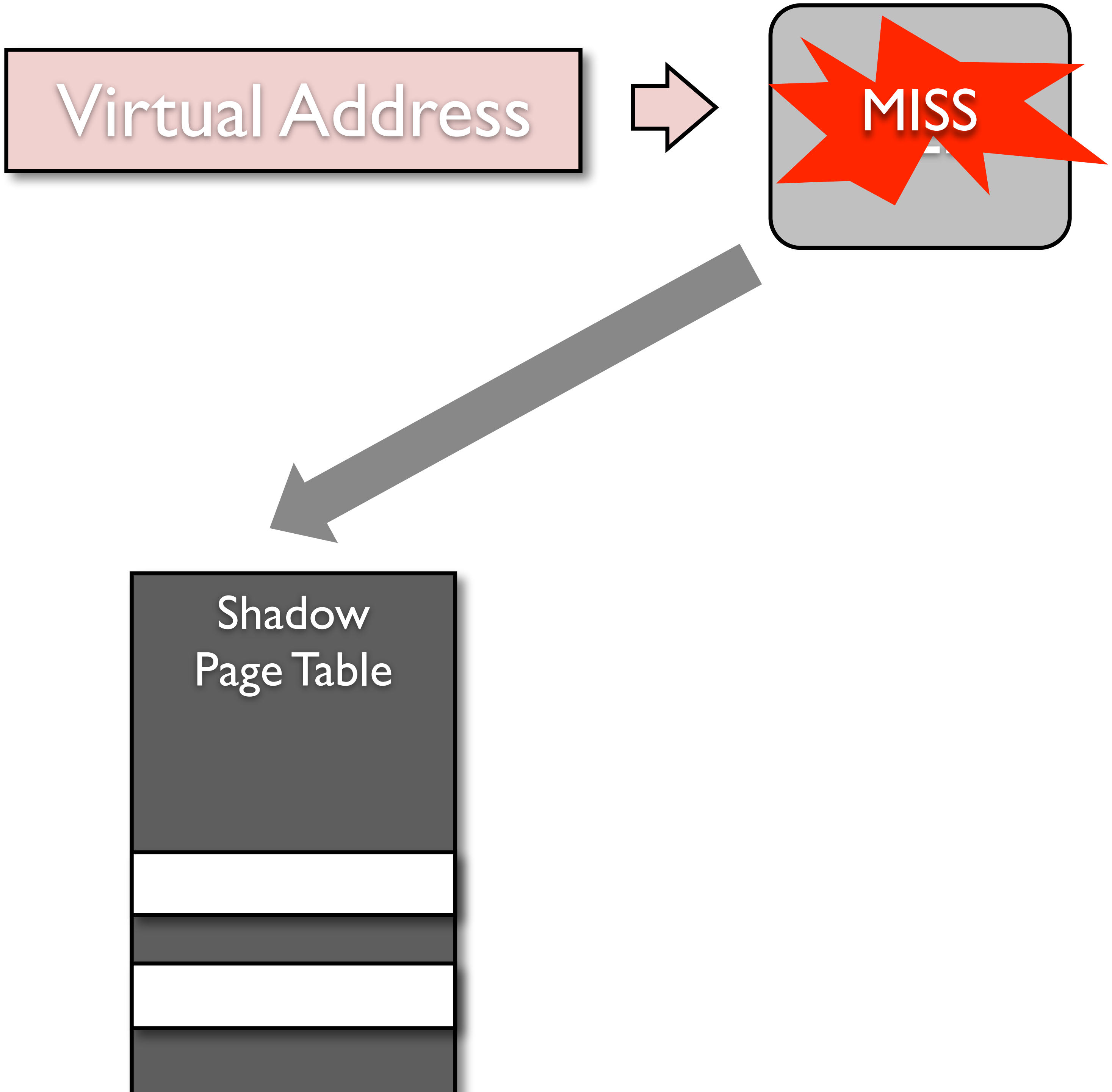
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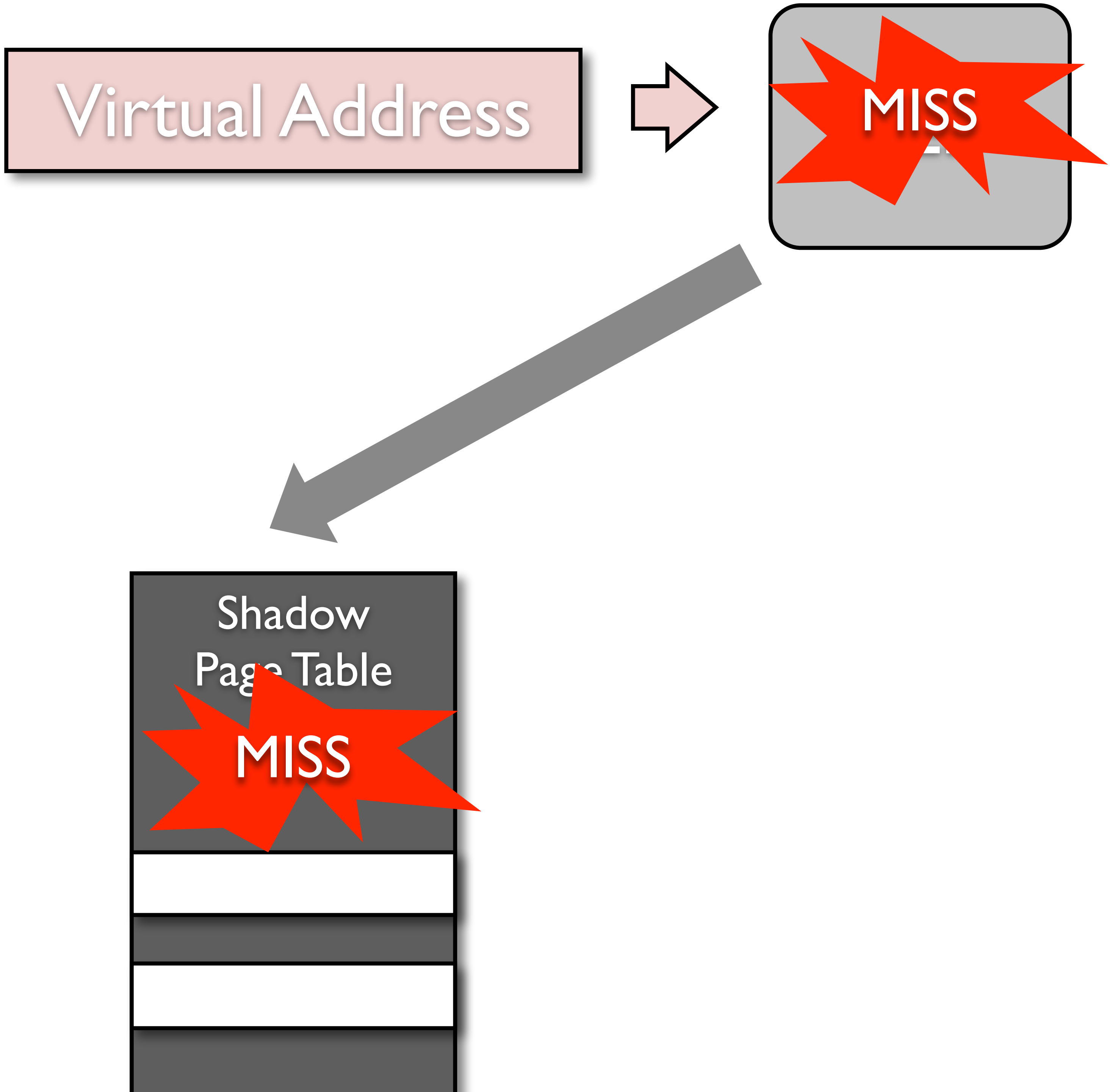

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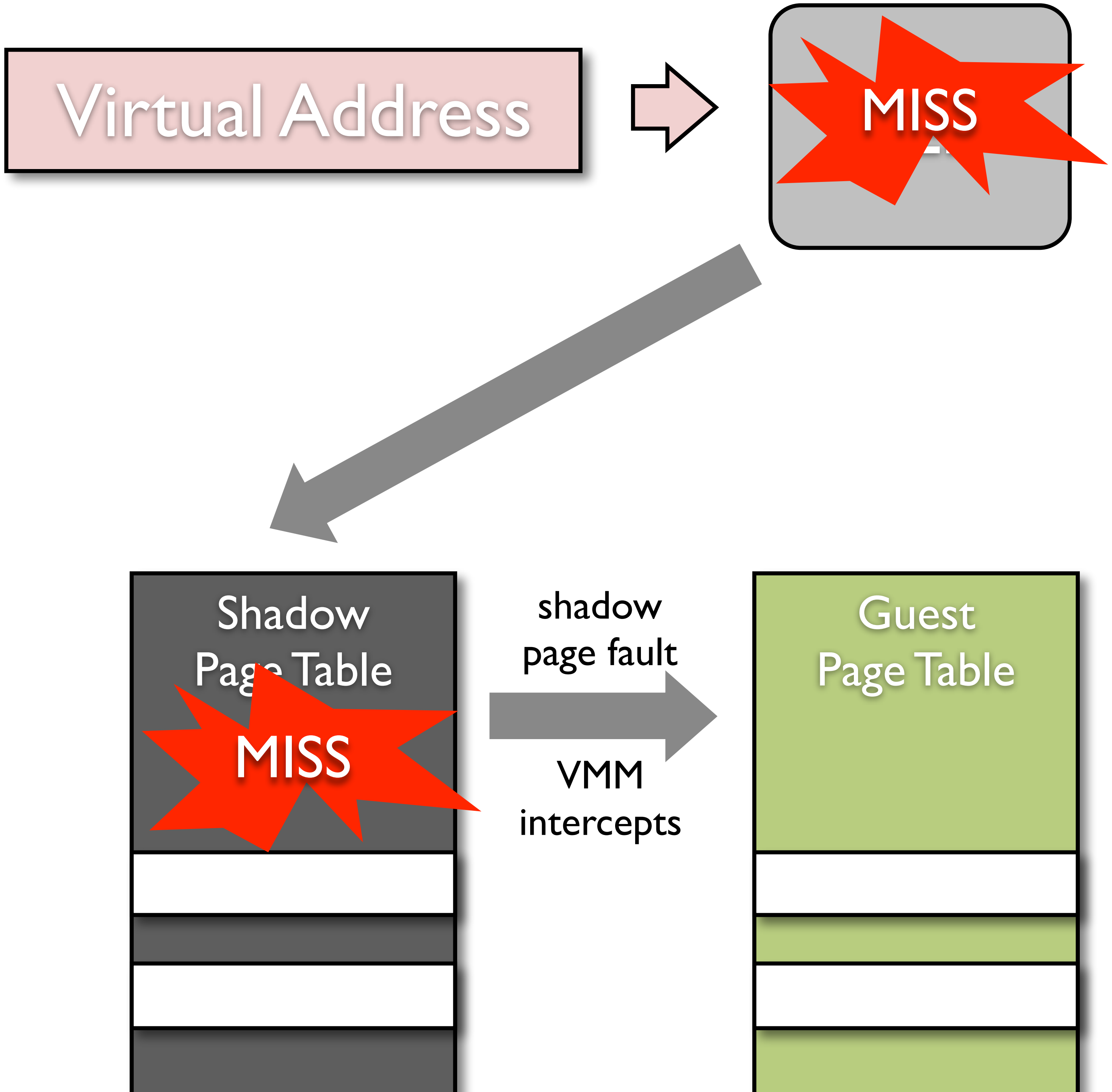

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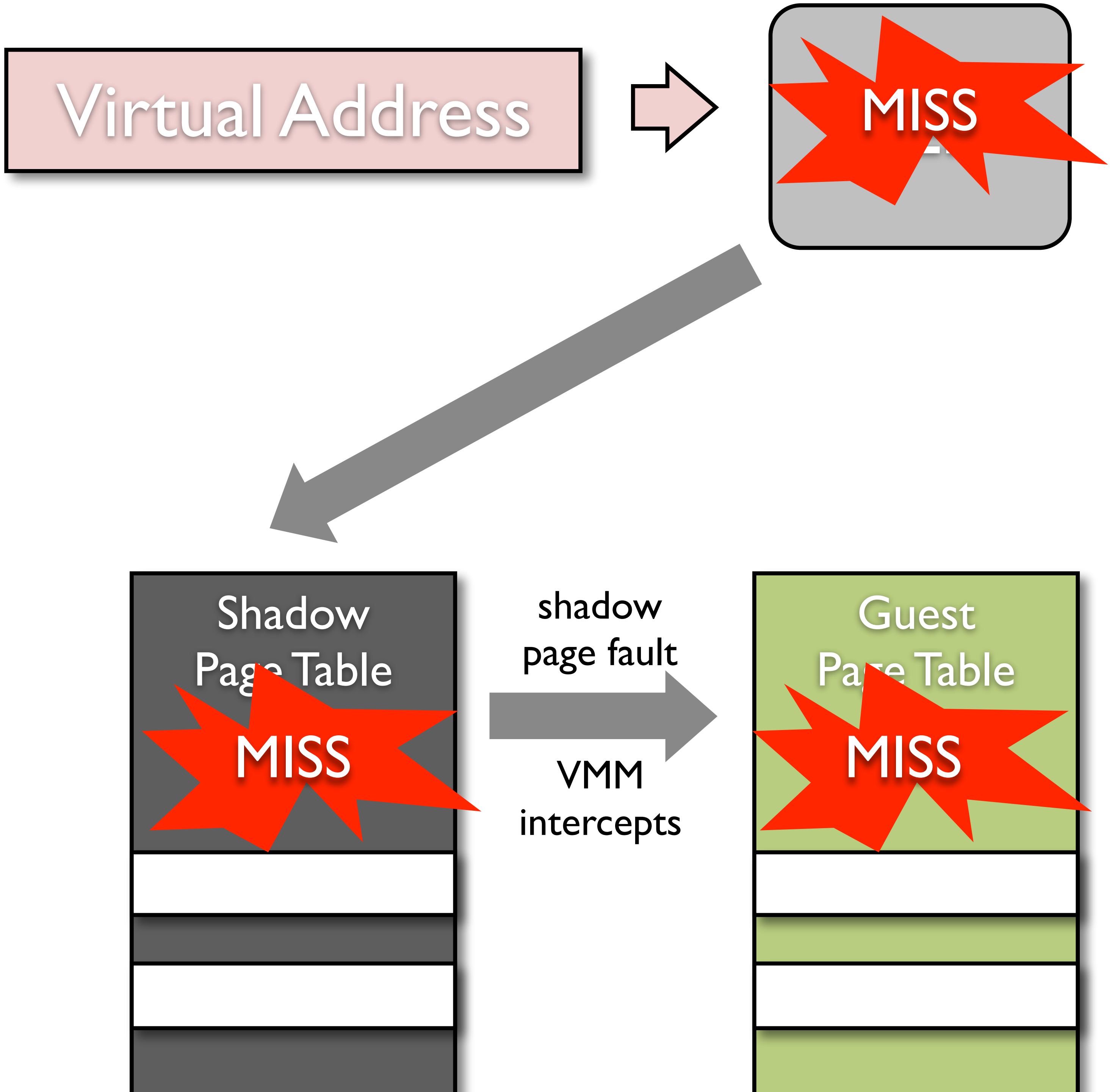

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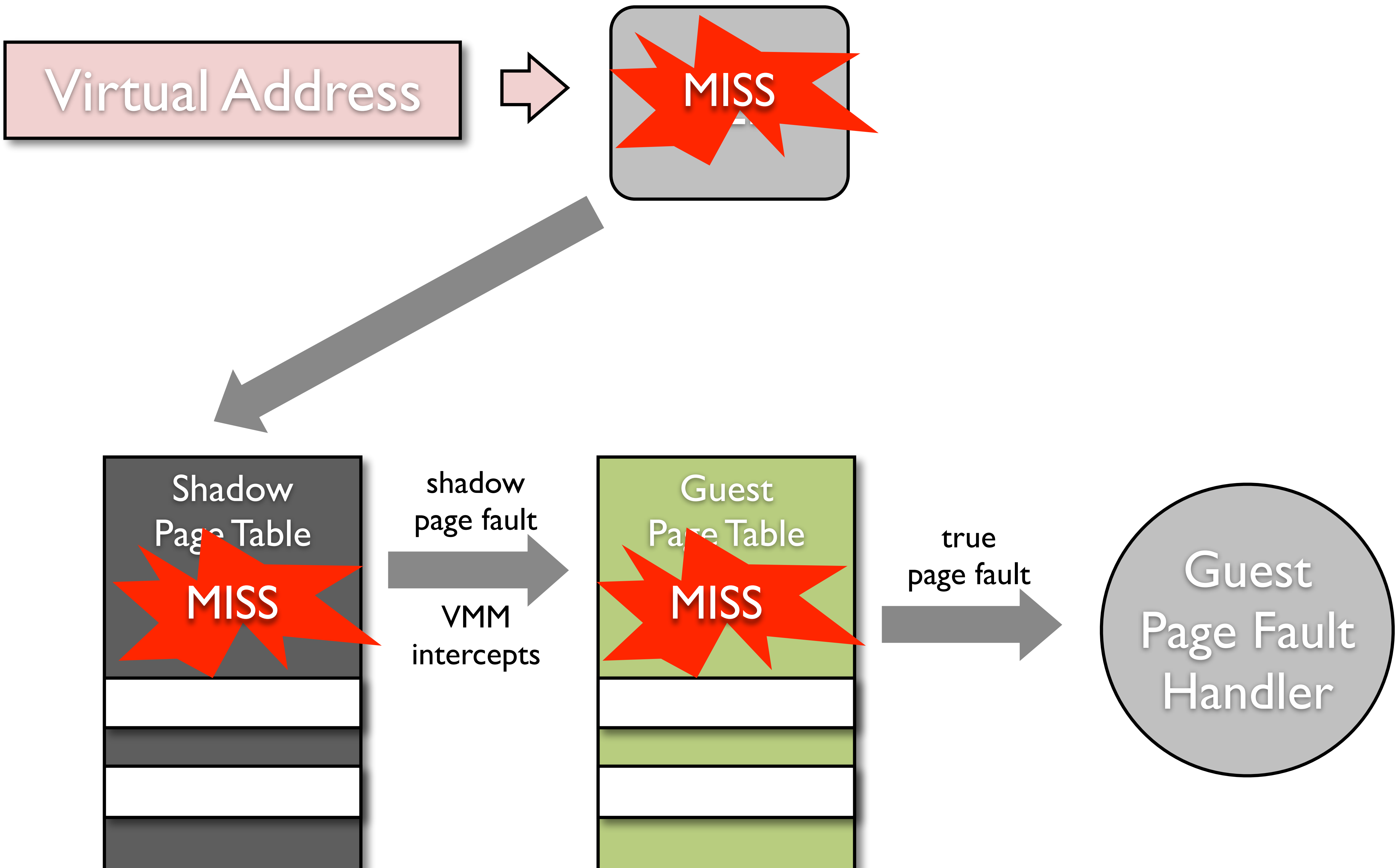

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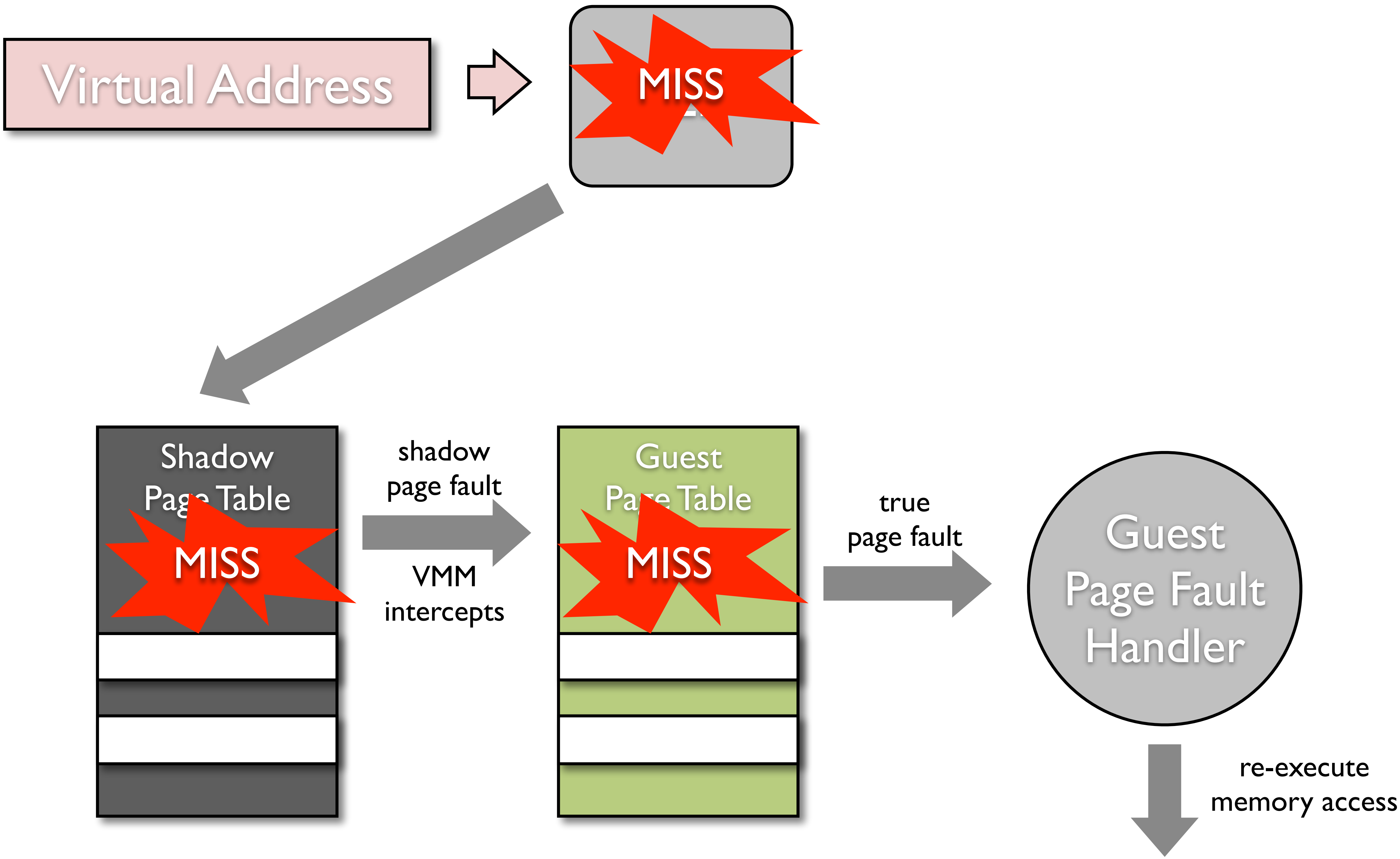

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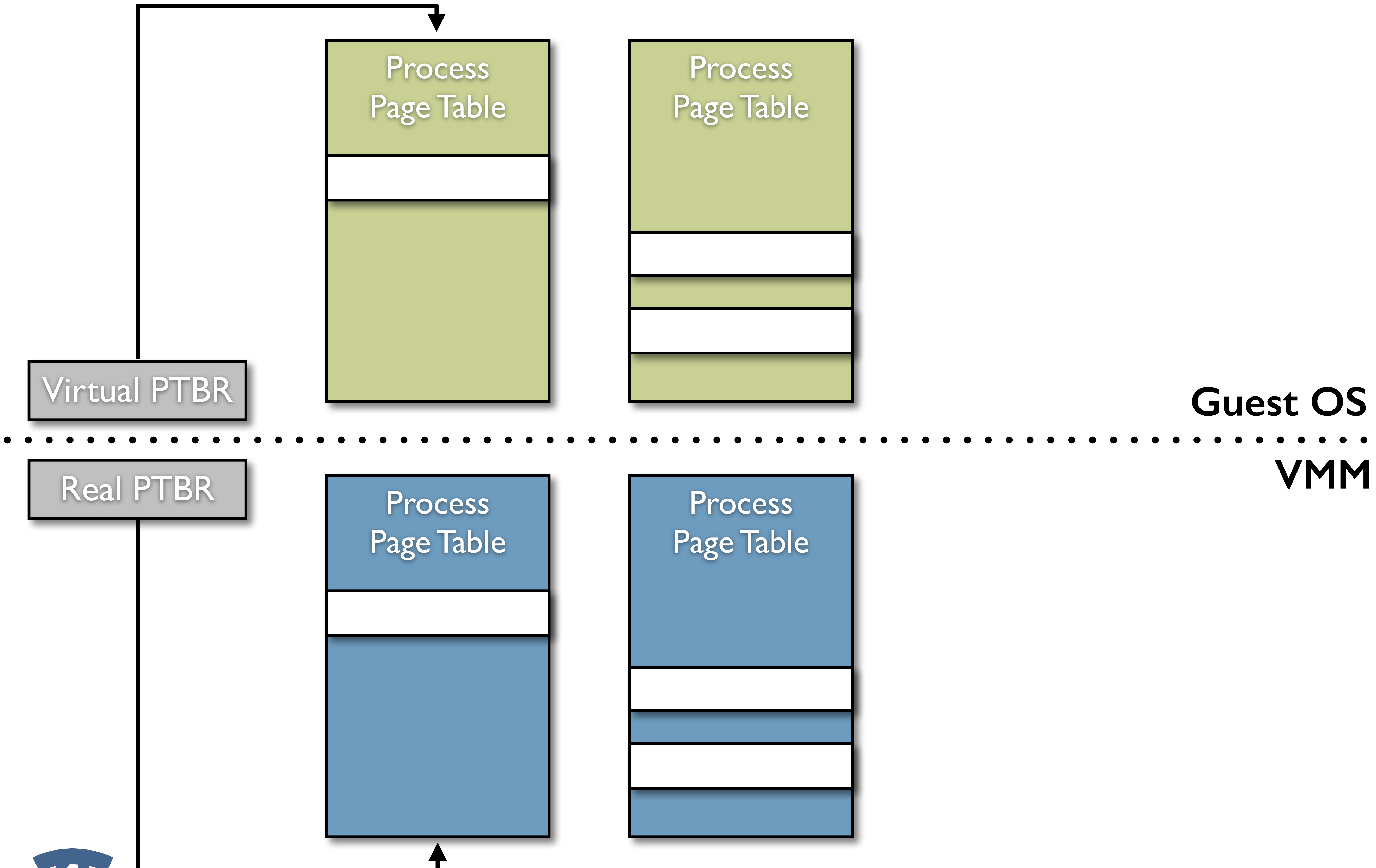

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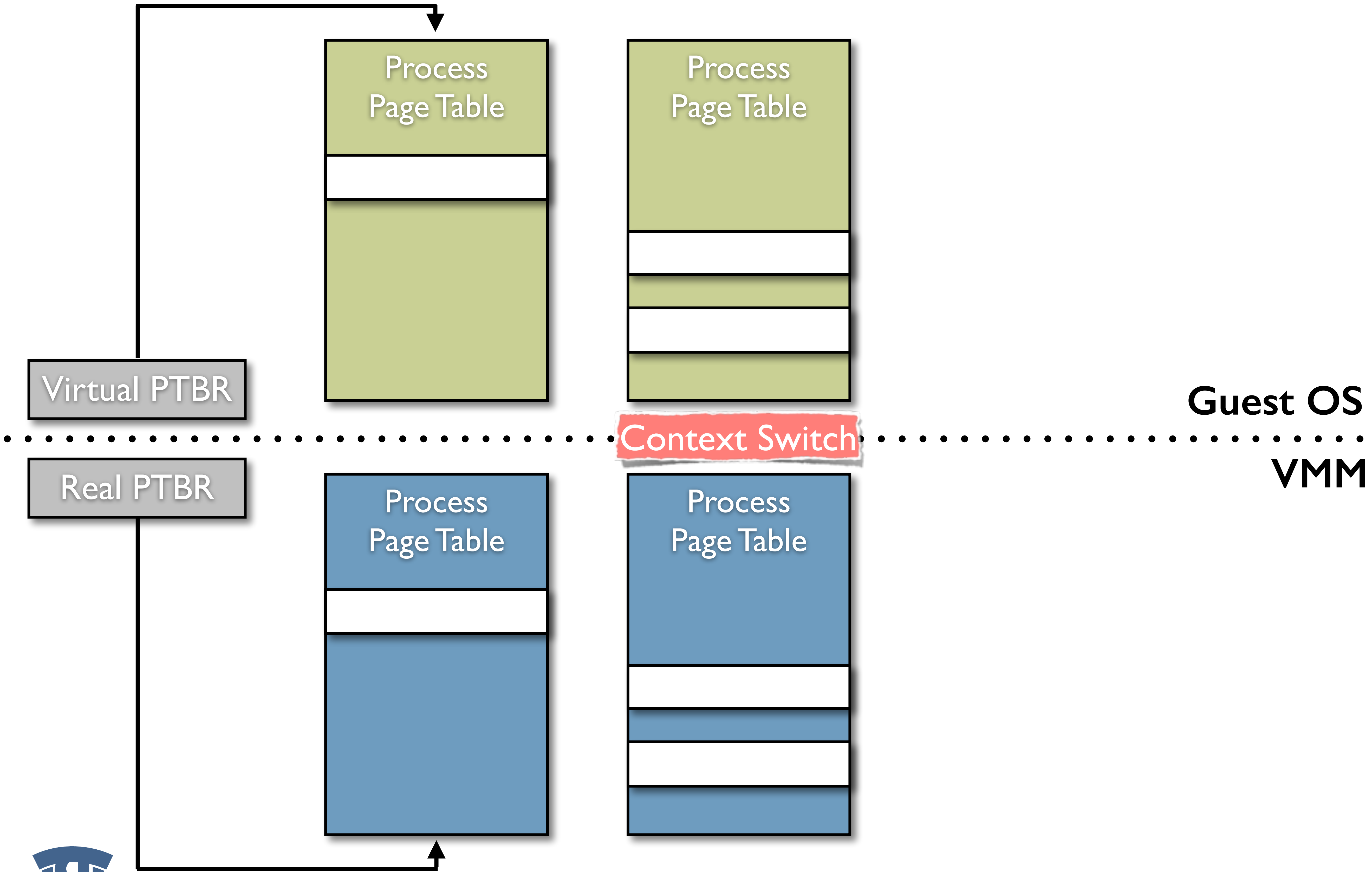

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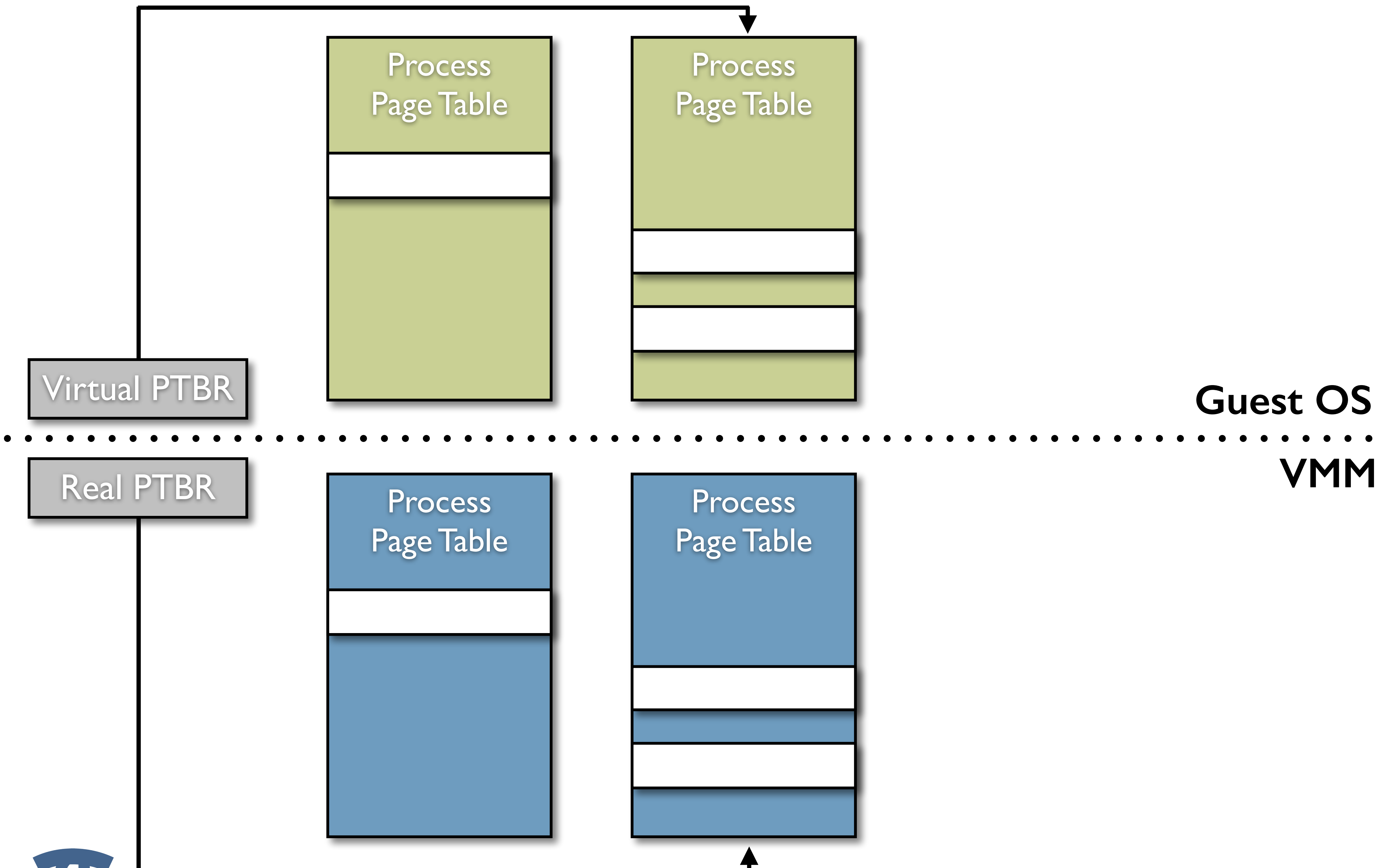

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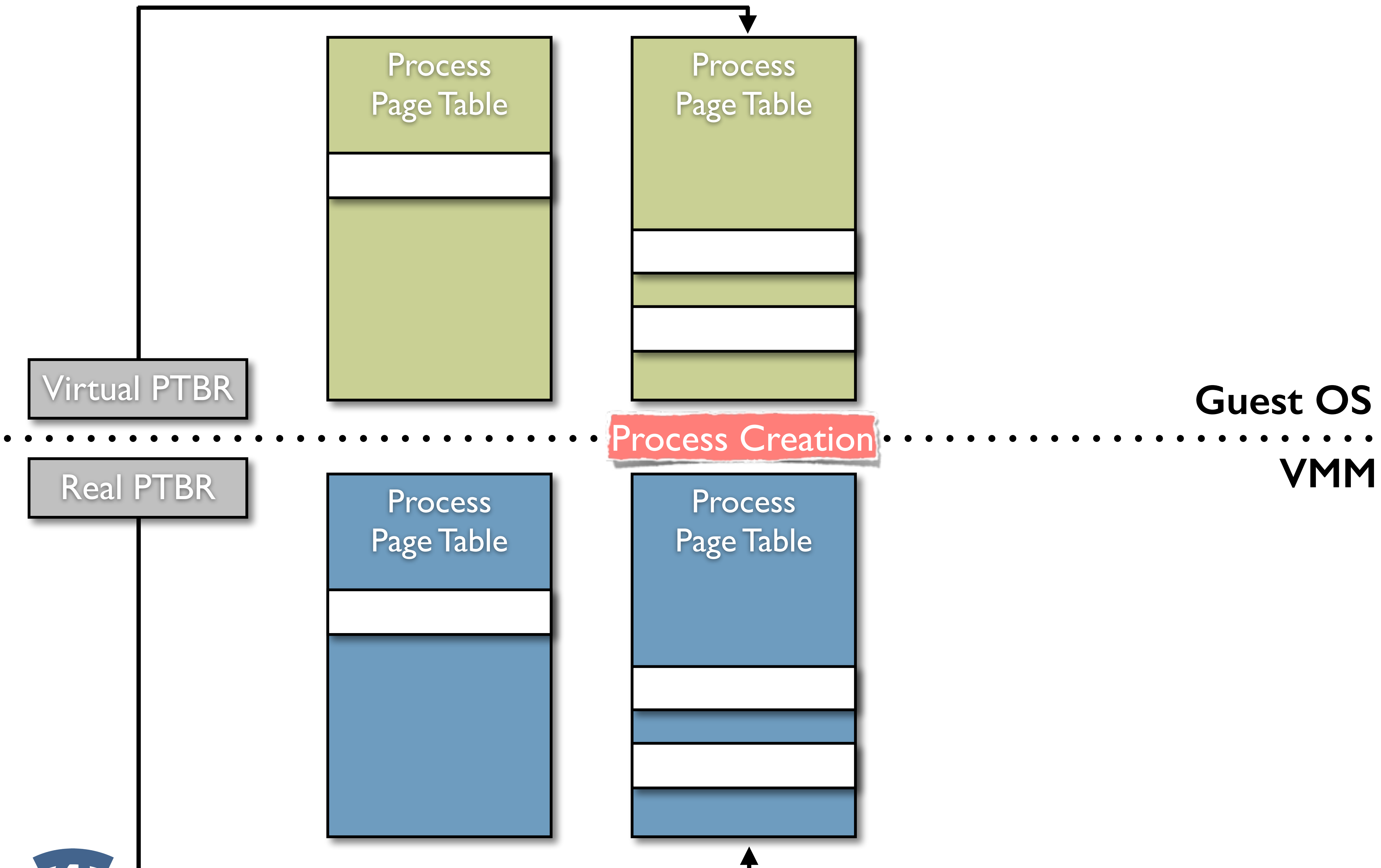

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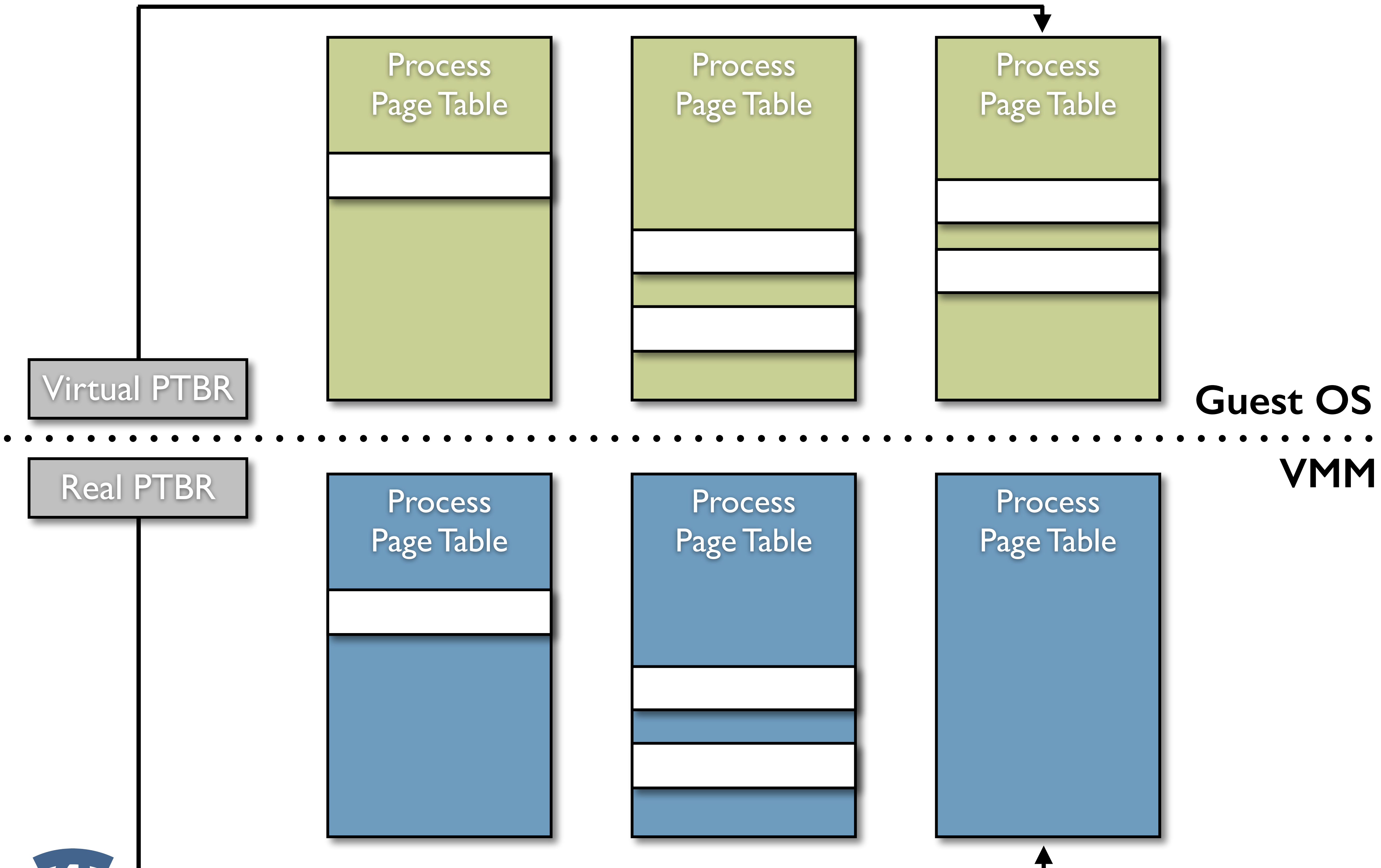

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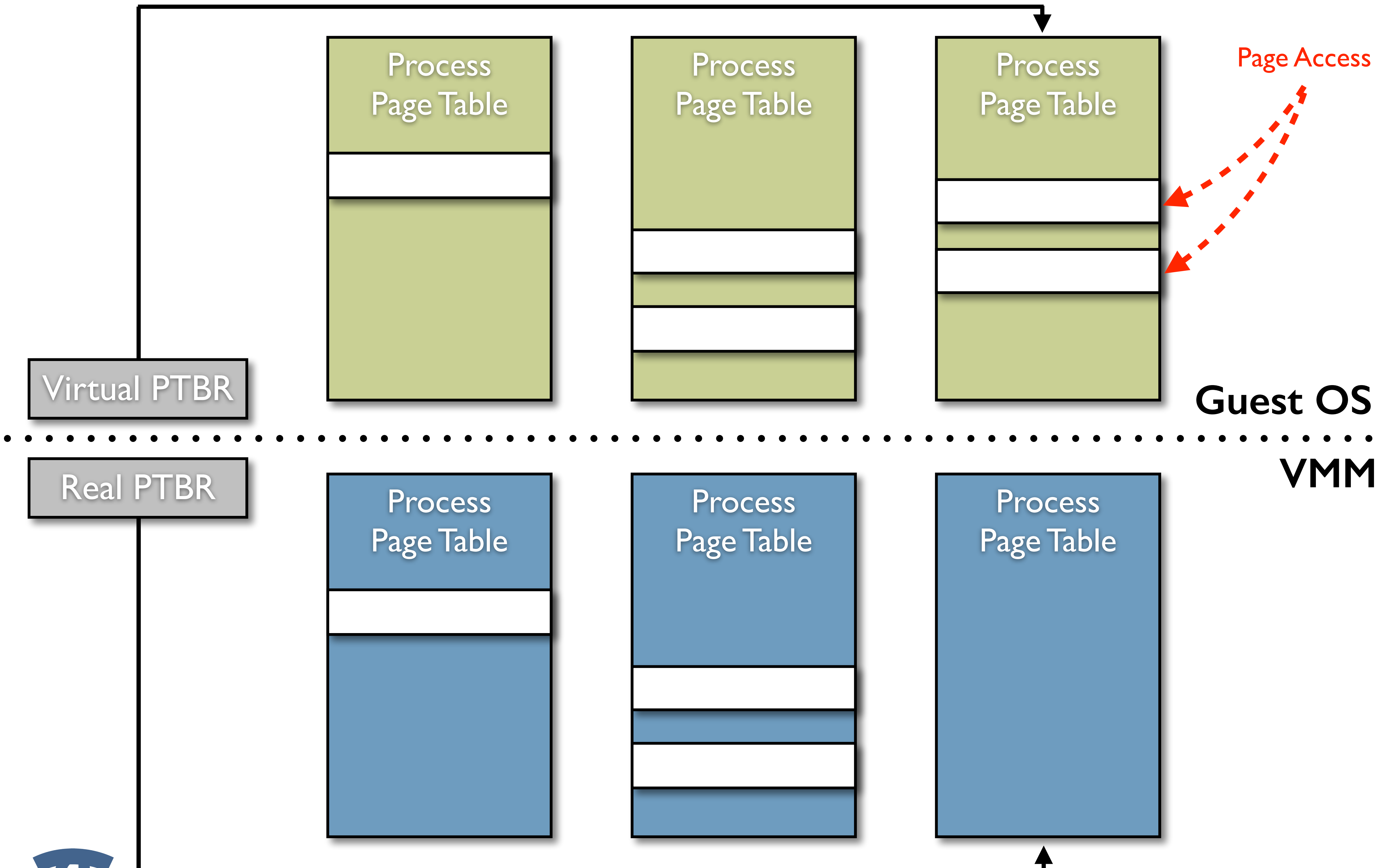

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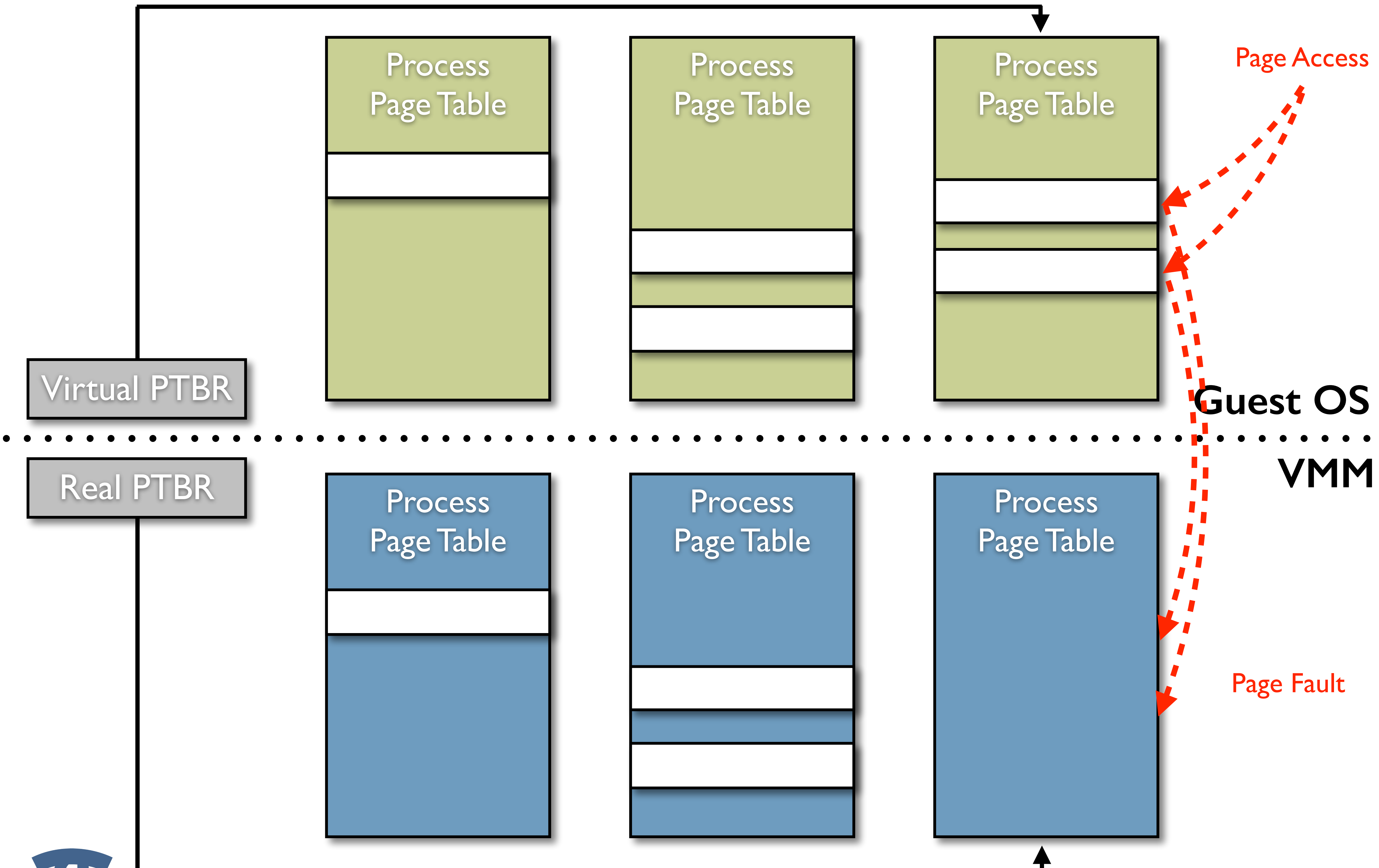

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