Virtual Machines

Concepts

- Virtualization:
  - Creation of flexible substitutes for actual resources.
    - The substitutes and their actual counterparts:
      - have same functions and external interfaces
      - differ in size, performance, cost etc.
    - Resources to virtualize
      - CPU
      - Memory
      - I/O

Concepts

- System Virtualization
  - System virtualization creates several virtual systems within a single physical one.
- VMM (or hypervisor)
  - Virtual machine monitor is the software layer providing the virtualization.
- VM
  - Virtual machine is the virtual systems running on top of VMM

Brief History

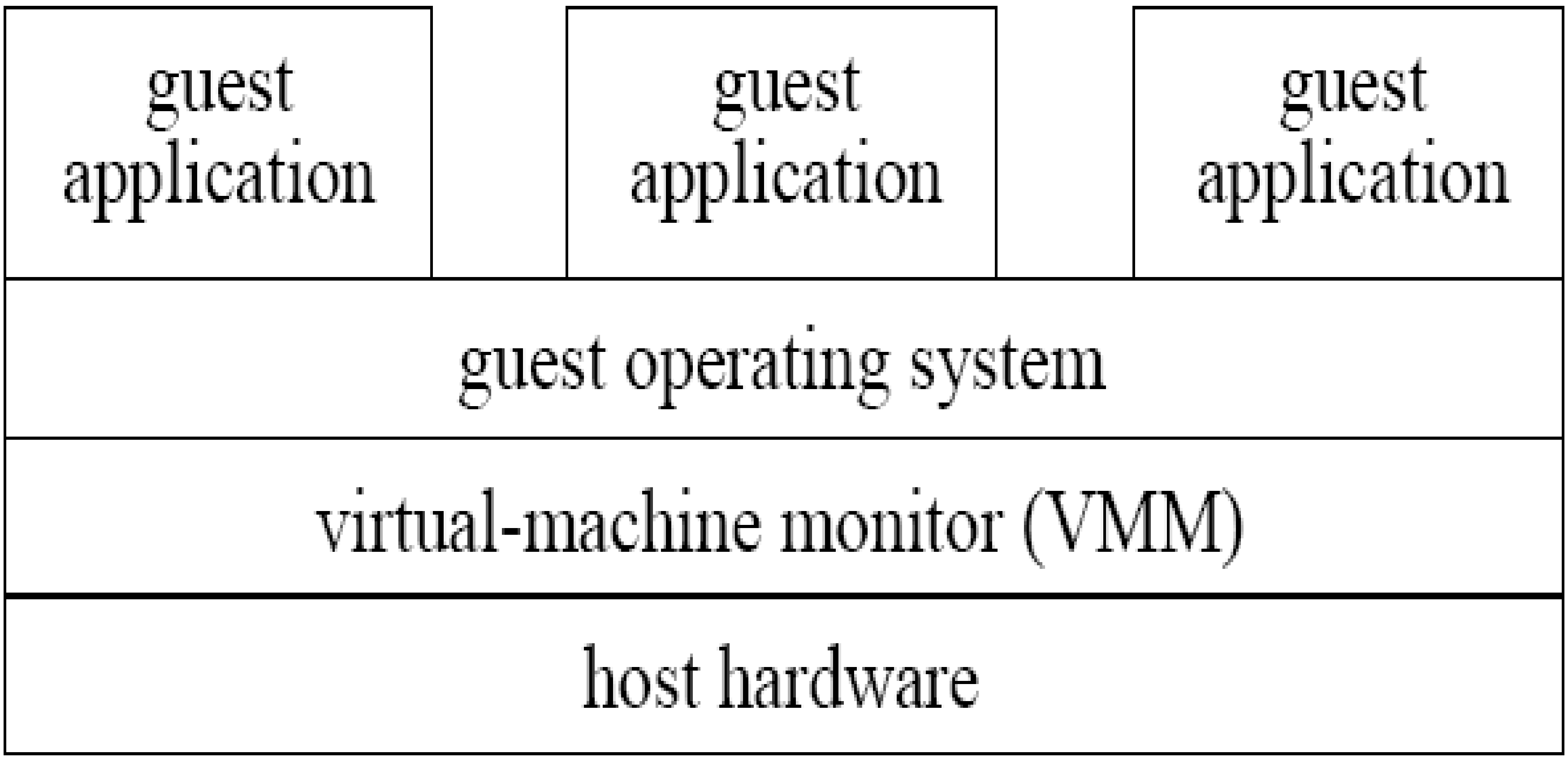
- 1960s, first introduced, for main frames
  - Motivation: hardware cost etc.
- 1970s, an active research area
- 1980s, underestimated
  - Multitask modern operating systems took its place
  - Decreasing in hardware cost
- late 1990s, resurgence: software techniques for x86 virtualization
  - Many applications: mixed-OS develop environment, security, fault tolerance etc.
- mid 2000s, hardware support from both Intel and AMD

Types of Virtualization

- Process virtualization (virtualize one process)
  - The VM supports an ABI: user instructions plus system calls
  - Dynamic translators, JVM, …
- OS or Namespace virtualization (multiple logical VMs that share share the same OS kernel)
  - Isolates VMs by partitioning all objects (not just files) into namespaces
  - Linux containers and vServer, Solaris zones, FreeBSD jails, Docker
- System (or full) virtualization (whole system: OS+apps)
  - The VM supports a complete ISA: user+system instructions
  - Classic VMs, whole system emulators (and many others we discuss in next slides)

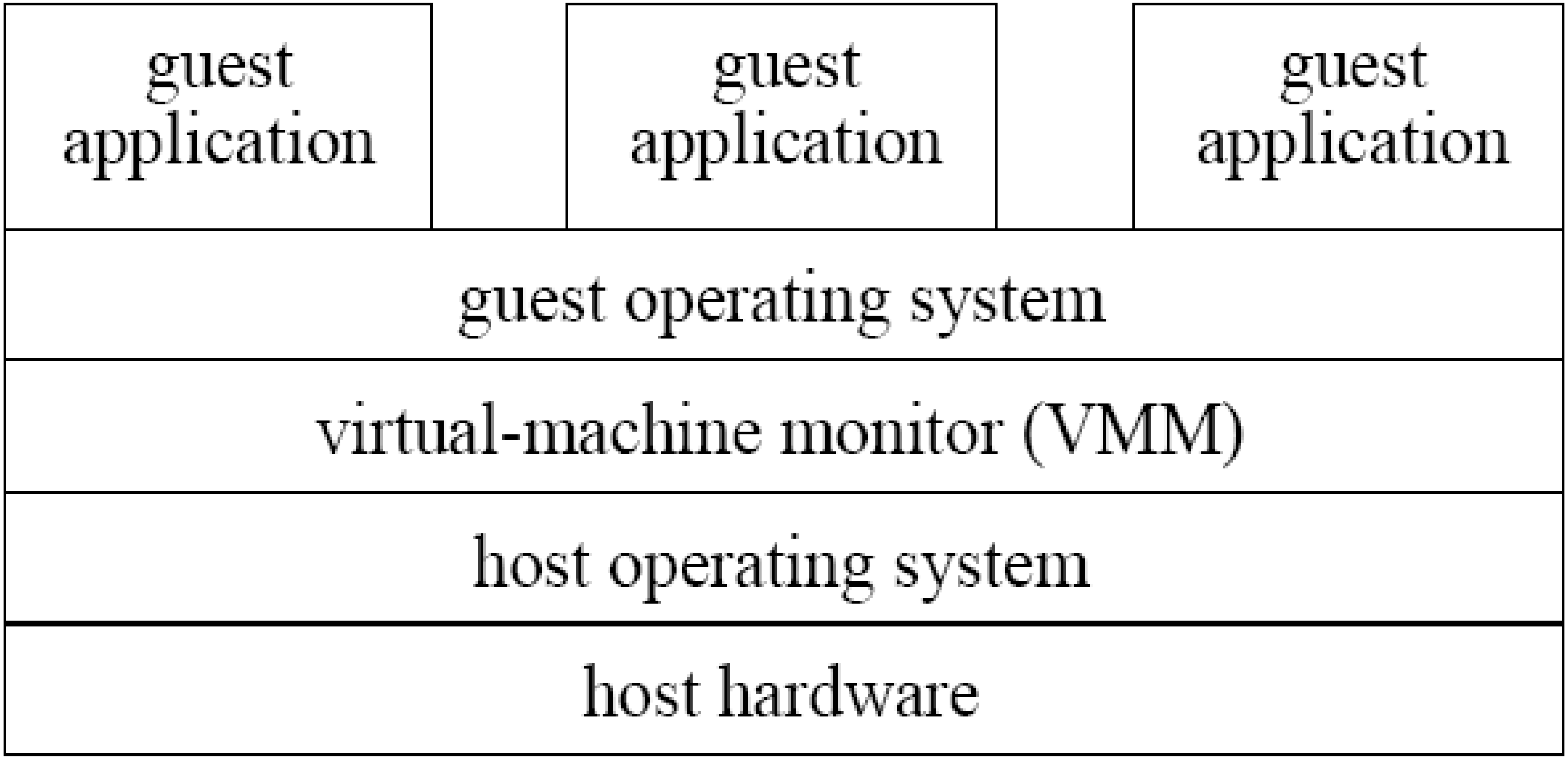
Architectures

- Type I: The VMM runs on bare hardware ("bare-metal hypervisor")

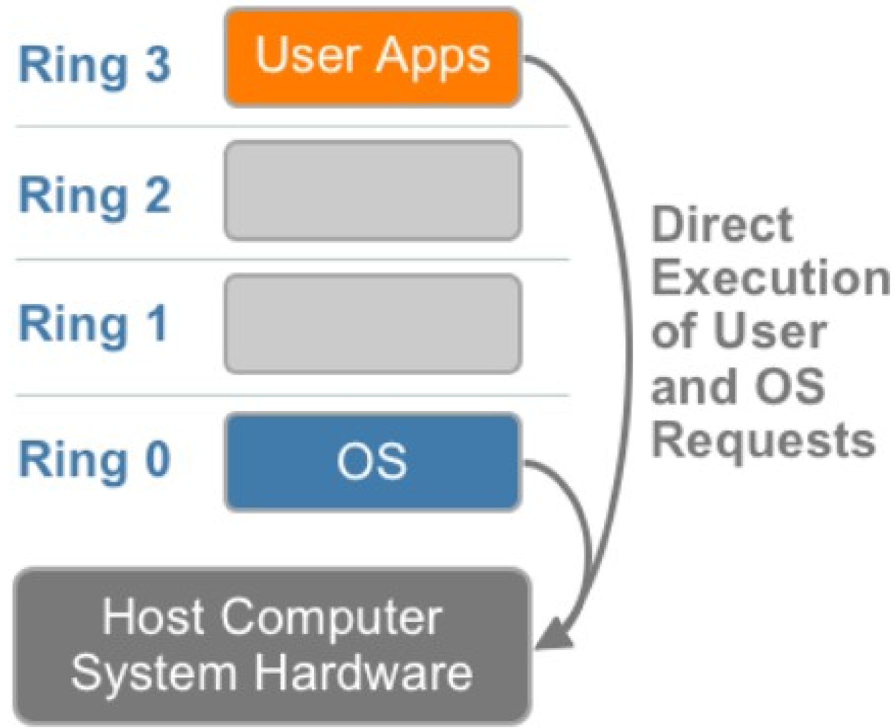


Architectures

- Type II: The VMM runs as an ordinary application inside host OS (hosted hypervisor)



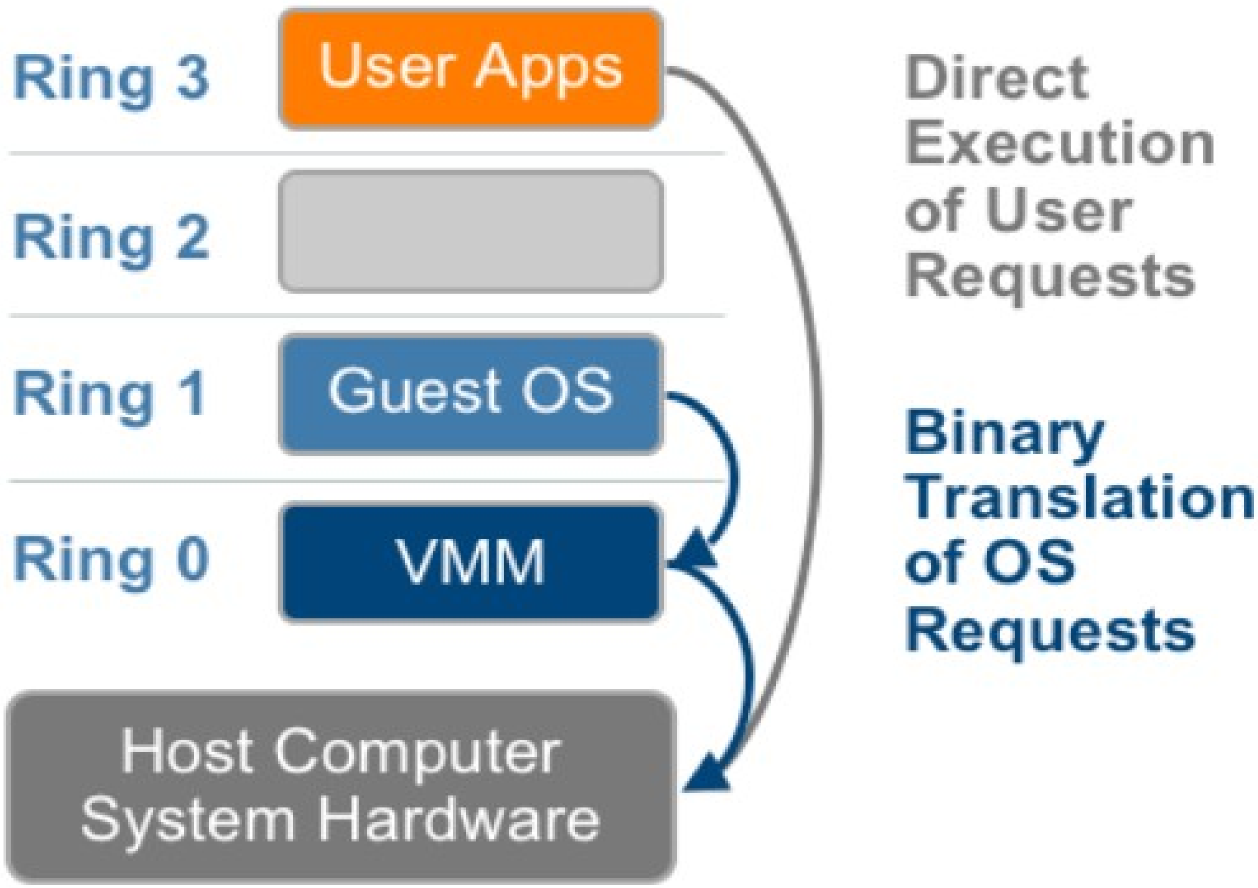
Key Issues in CPU Virtualization



- Protection levels
  - Ring 0 (most privileged)
    Ring 3 (user mode)
- Requirement for efficient/ effective virtualization
  - Privileged instructions
    - Trap if executed in user mode
  - Sensitive instructions
    - affect important "system state"
  - If privileged==sensitive, can support efficient "trap and emulate" approach
    - Virtualized execution = native execution+exception handling code that emulates privileged instructions
- For x86, not all sensitive instructions are privileged
  - Some instructions simply exhibit different behaviors in user and privileged mode

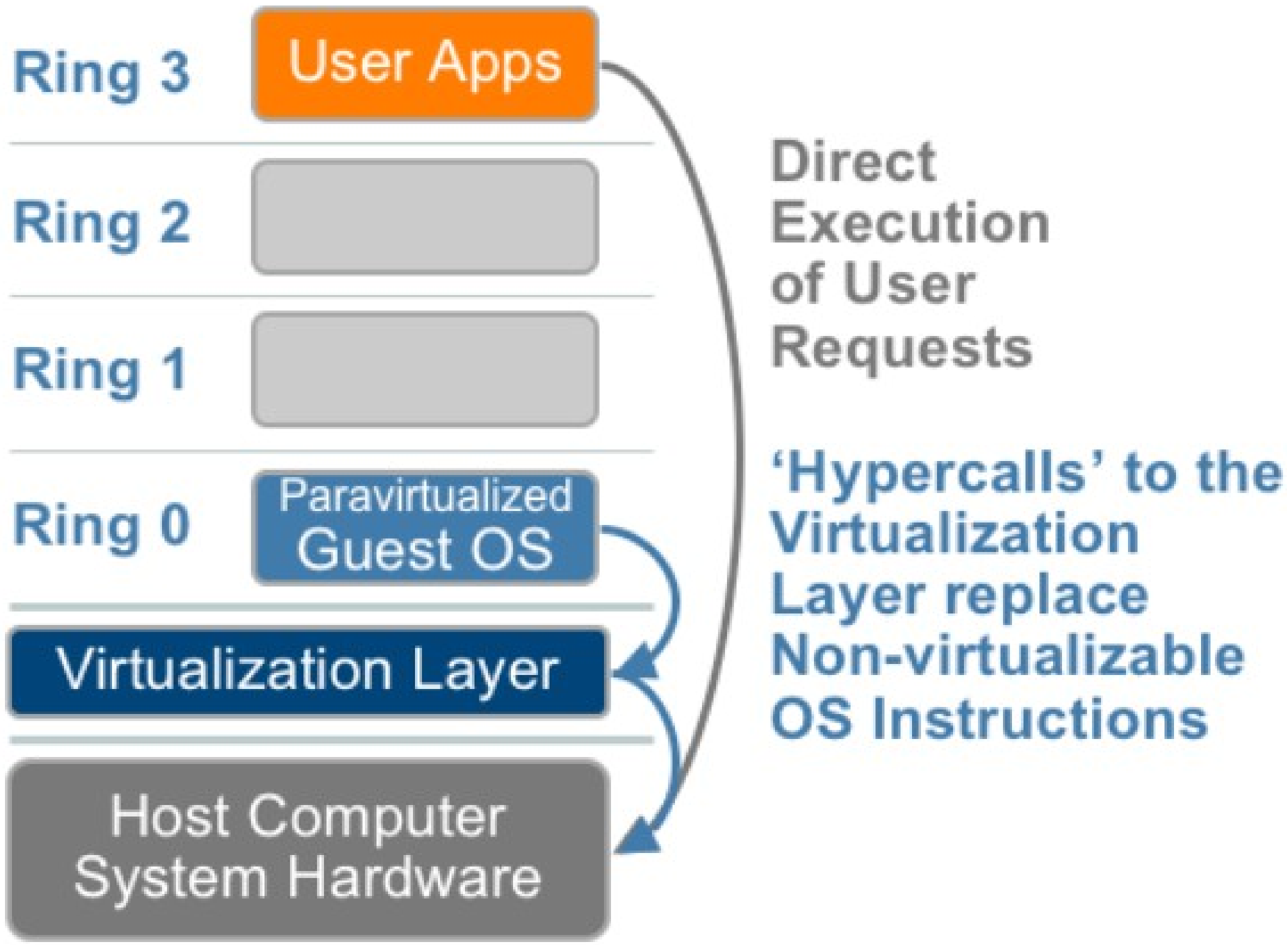
Virtualization Approaches

- Full virtualization using binary translation
  - Problem instructions translated into a sequence of instructions that achieve the intended function
  - Example: VMware, QEMU



Virtualization Approaches

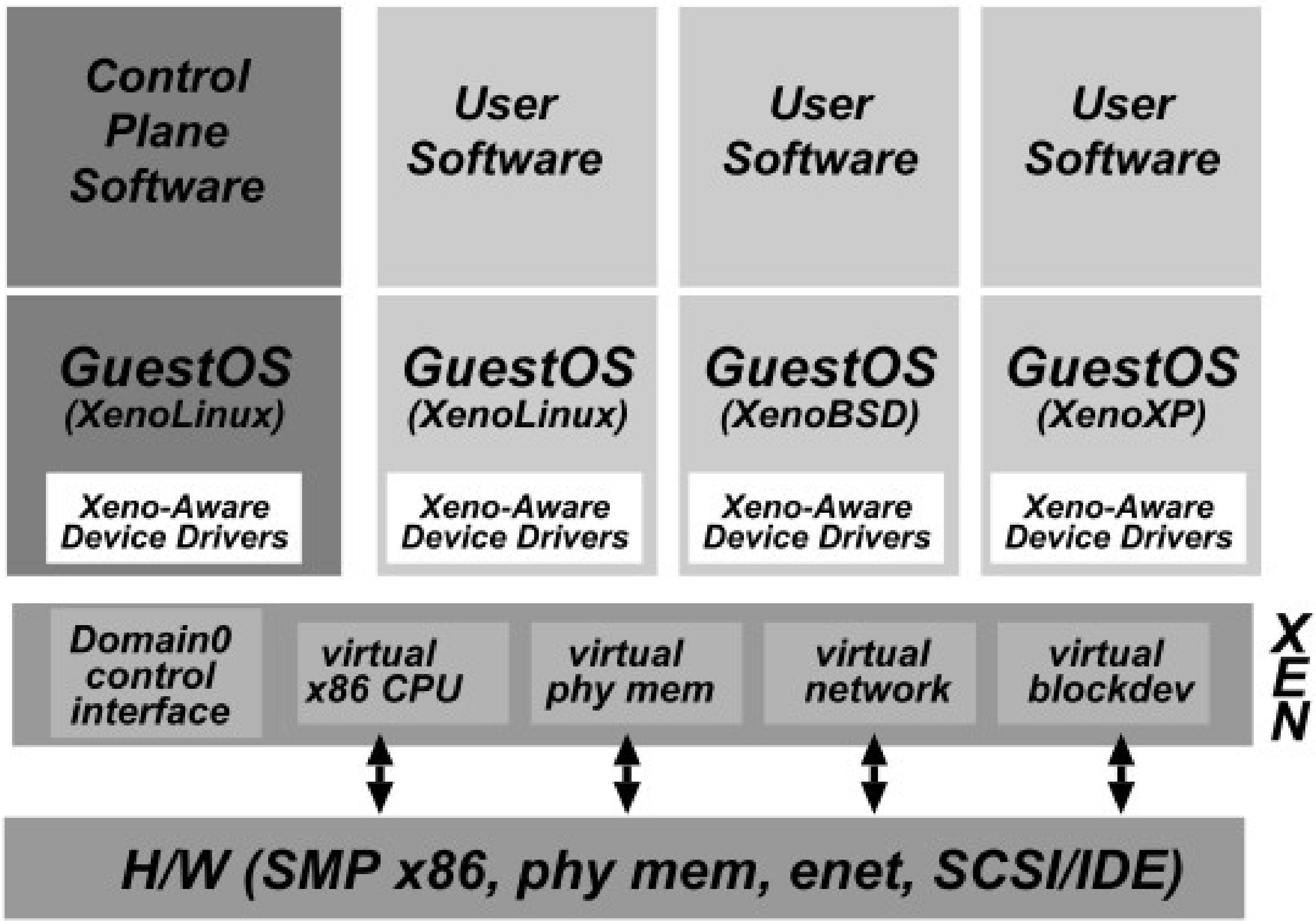
- Paravirtualization: OS modified to run on VMM
  - Example: Xen



Paravirtualization

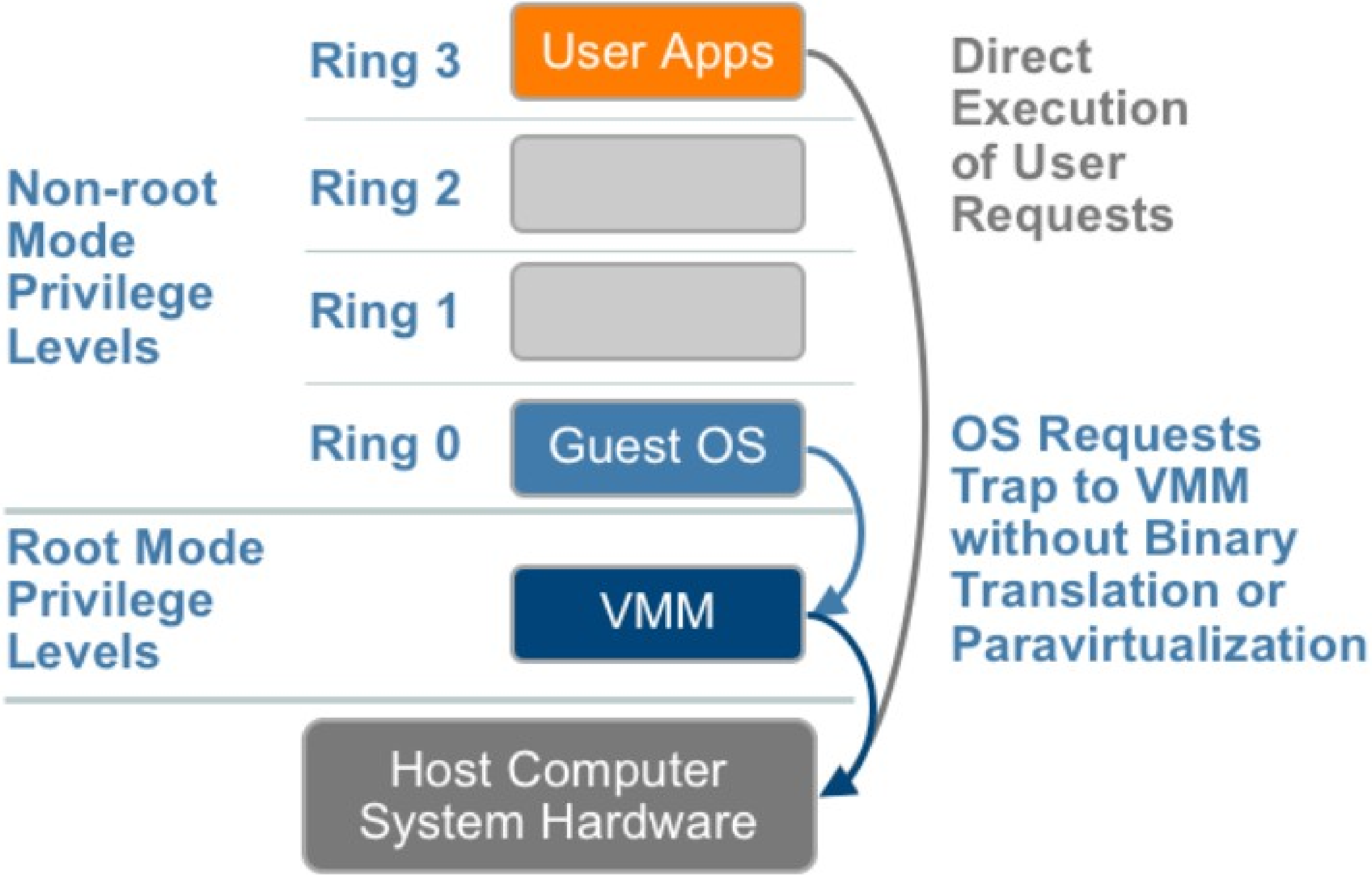
- No longer 100% interface compatible, but better performance
  - Guest OSes must be modified to use VMM's interface
  - Note that ABI is unchanged
    - Applications need not to be modified
- Guest OSes are aware of virtualization
  - privileged instructions are replaced by hypervisor calls
  - therefore, no need for binary translation

Xen and the Art of Virtualization



Virtualization Approaches

- Hardware-assisted virtualization



Hardware-assisted Virtualization

- Processor
  - AMD virtualization (AMD-V)
  - Intel virtualization (VT-x)

AMD-V: CPU virtualization

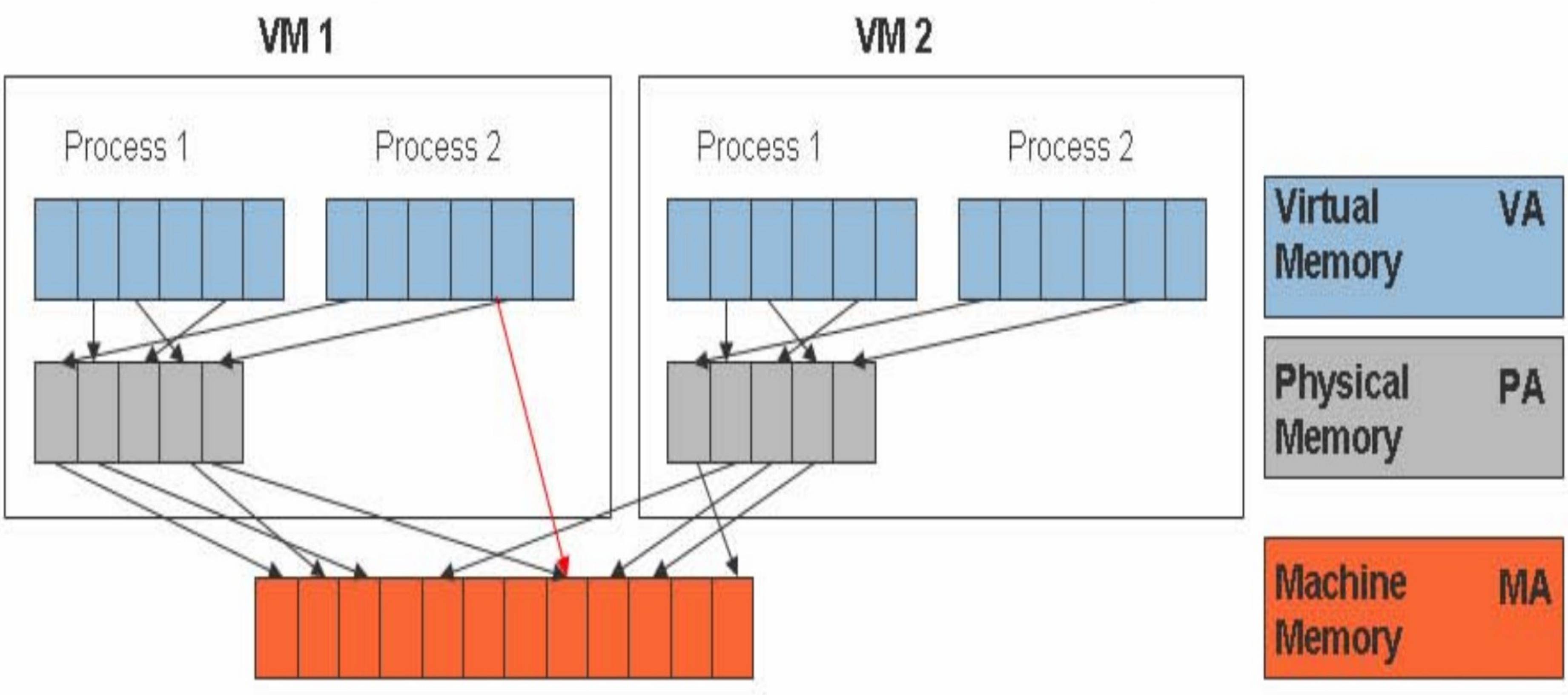
- Separates CPU execution into two modes
  - hypervisor executes in host mode
  - all VMs execute in guest mode
- Both hypervisor and VMs can execute in any of the four rings
- Hypervisor can
  - explicitly switch from host mode to guest mode
  - specify which events (e.g. interrupts) cause exist from guest mode

Memory Virtualization

- Access to MMU needs to be virtualized
  - Otherwise guest OS may directly access physical memory and/or otherwise subvert VMM
- Physical Memory is divided among multiple VMs
  - Two levels of translation
    - Guest OS: guest virtual addr → guest physical addr
    - VMM: guest physical addr → machine addr

Memory Virtualization

- Shadow page table needed to avoid 2-step translation
  - When guest attempts to update, VMM intercepts and emulate the effects on the corresponding shadow page table



AMD-V: Memory Virtualization

- CPU is aware of
  - the existence of VM
  - two-level address translation
- AMD's nested page table
  - (Intel VT-x has a similar scheme called Extended Page Table)
  - managed by VMM
  - guest physical addr -> machine addr
  - guest OS directly updates its guest page table
  - therefore, no need for a shadow page table

I/O Virtualization

- The VMM
  - intercepts a guest’s I/O action
  - converts it from a virtual device action to a real device action

Security Applications

- Honeypot systems and Malware analysis
  - VM technology provides strong isolation that is necessary to run malware without undue risks
    - Strong resource isolation: CPU, memory, storage
    - Snapshot/restore features to speed up testing and recovery
- High-assurance VMs
  - On a single workstation, can run high assurance VMs that support some security functions, but may not provide general-purpose functions
    - single-purpose VM scheme facilitates stricter security policies
    - In contrast, security policies that are compatible with the range of desktop applications being used today will likely be too permissive.

Security Applications

- Protection from compromised OSes
  - Modern OSes are too complex to secure
  - Malware-infested OS may subvert security software (virus and malware scanners)
  - Instead, rely on VMM
    - run malware and rootkit detection techniques in VMM
    - enforce security properties from within the VMM

Security Challenges

- Virtualization leads to co-tenancy
  - VMs belonging to distinct principals use the same hardware
    - Strong isolation is necessary or else attacks become too easy
      - Containers don’t offer enough security if some principals can be downright malicious
    - Even with strong isolation, provide increased opportunities for side-channel attacks
    - Denial of service is difficult to prevent
      - But often, it is not a problem in practice as bad behavior is expensive, and/or is detected and the culprit punished

Docker Security

- Isolation of containers
  - namespaces: each container cannot see entities (files, processes, pids, network interfaces, …) in other containers
  - cgroup: enables resource accounting and limiting --- including CPU, memory, disk I/O, etc.
    - one bad container cannot use up all resources
- Container infrastructure and services (docker daemon)
  - containers can share files/directories with the host OS, but this can be very dangerous, e.g., allow root user in a container to change critical host OS files
  - administrative services (e.g., creation of containers) can be abused, so interface to docker daemon should be restricted
- Limit further using Linux capabilities
  - programs running with containers typically don't need root privilege
  - we can use Linux capabilities to take away almost all of the power of the root