Virtualization for Embedded Systems
Lecture for the Embedded Systems Course
CSD, University of Crete (April 27, 2015)

- Manolis Marazakis (maraz@ics.forth.gr)

FORTH-ICS Institute of Computer Science (ICS)
Foundation for Research and Technology – Hellas (FORTH)

Virtualization Definitions

- **Virtual Machine:** a software-based implementation of real (hardware-based) computer
  - In its pure form, supports booting and execution of unmodified OSs and apps

- **Virtual Machine Monitor ("hypervisor"):** the software that creates and manages the execution of virtual machines
  - A VMM is essentially a simple operating system

Virtualization Use-cases

- Enterprise server (workload) consolidation
  - Run at most one service per machine (sysadm best practice) →run one service per VM
- Legacy software systems
- Virtual desktop infrastructure (VDI)
- Compute clouds
  - Large-scale, hosted cloud computing (e.g., Amazon EC2)
  - VM as a convenient container and sandbox
- End-user virtualization (e.g. S/W testing & QA, OS research)
- Embedded (e.g. smartphones)

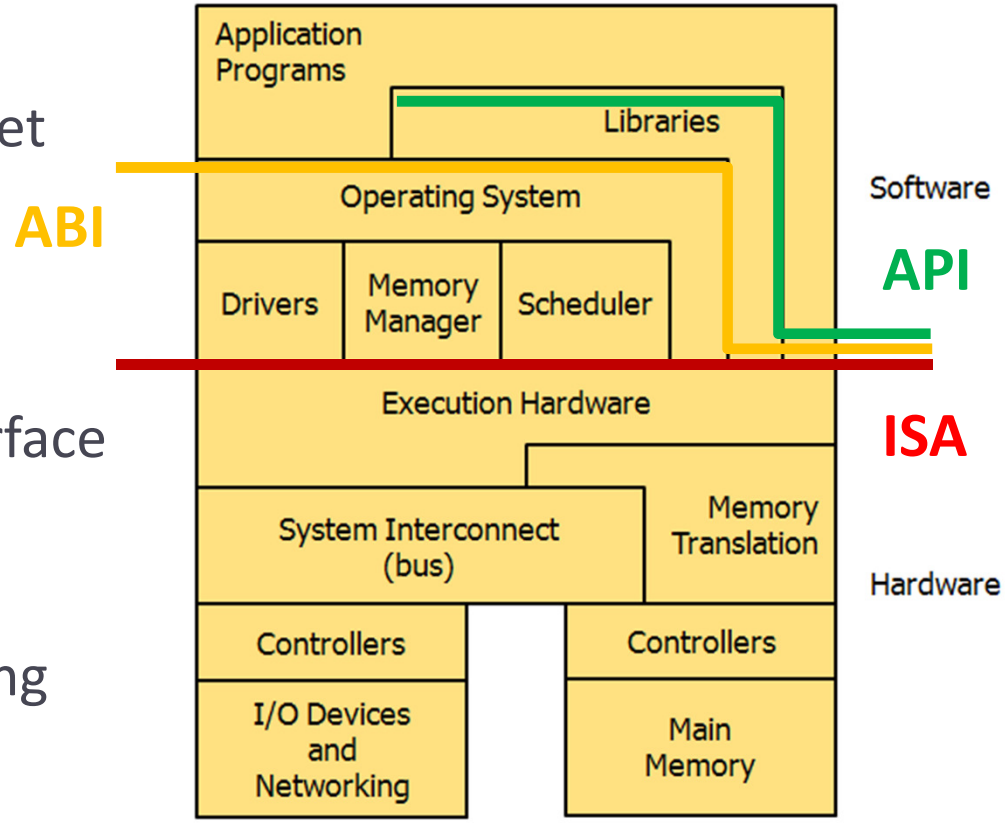
How does virtualization work, in detail ?

Lecture Outline

- Abstraction, system interfaces and implementation layers
  - ISA, ABI, API
- Virtual Machine Taxonomy
  - Process virtual machines
    - Multiprogrammed systems
    - Emulators and dynamic binary translation
    - High-level-language virtual machines
  - System virtual machines
    - “Classic” virtual machines
    - Hosted virtual machines
    - Whole-system virtual machines
- Key virtualization techniques

Computer systems are built on levels of abstraction

- Different perspectives on what a "machine" is
  - OS → ISA: Instruction Set Architecture
    - h/w – s/w interface
  - Compiler → ABI: Application Binary Interface
    - User ISA + OS calls
  - Application → API: Application Programming Interface
    - User ISA + Library calls



By Glenford Myers (1982)

Virtualization Definitions

- Virtualization
  - A layer mapping its visible interface and resources onto the underlying layer or system on which it is implemented
  - Purposes: abstraction, replication, isolation
- Virtual Machine (VM)
  - An efficient, isolated duplicate of a real machine
    - Programs should not be able to distinguish between execution on real or virtual H/W (except for: fewer/variable resources, and device timing)
    - VMs should execute without interfering with each other
    - Efficiency requires that most instructions execute directly on real H/W
- Hypervisor / Virtual Machine Monitor (VMM)
  - Partitions a physical machine into multiple “virtual machines”
    - Host : machine and / or software on which the VMM is implemented
    - Guest : the OS which executes under the control of the VMM

OS vs Hypervisor (VMM)

- Hypervisor / Virtual Machine Monitor (VMM)
  - Software that supports virtual machines on a physical machine
  - Determines how to map VM resources to physical ones
  - Physical resources may be time-shared, partitioned, or emulated
- The OS has complete control of the (physical) system
  - Impossible for >1 operating systems to be executing on the same platform
  - OS provides execution environment for processes
- Hypervisor (VMM) “virtualizes” the hardware interface
  - GuestOS’s do not have complete control of the system
  - VMM provides execution environment for OS
    - “virtual hardware”

What needs to be emulated for a VM? [Hardware]

- CPU and memory hierarchy
  - ISA, Register state, Memory state
  - Privilege levels, Exceptions/Traps, Interrupts
- Memory Management Unit (MMU)
  - Page tables, segments → virtual memory support
  - Controlled via special registers, and via page tables
- Platform
  - Interrupt controller, timers, peripheral buses
- Firmware (BIOS)
- Peripheral devices
  - Disk, network interface, serial line
  - Programmed I/O, Direct Memory Access (DMA)
  - Events delivered to software via polling or interrupts

Hardware is not (commonly) designed to be multiplexed → Loss of isolation

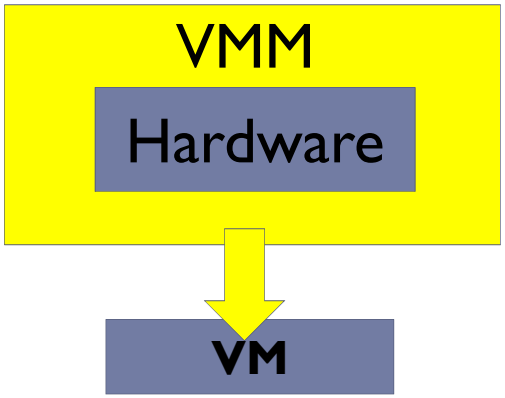
What needs to be emulated for a VM? [OS, App]

- OS
  - OS issues instructions to control hardware devices
  - … interacts with hardware devices using “sensitive” instructions
  - Allocate and manage hardware resources on behalf of programs
  - … OS runs at higher privilege level than applications
  - Expose system call interface to applications
  - … implemented using low-level H/W interfaces
- Application
  - Relies on the system call interface, runs in unprivileged mode
  - Special instruction(s) to call into OS code
  - OS provides a program with the illusion of its own memory
    - Virtual address spaces (implemented via MMU) → isolation
      - from OS and other App’s
  - Most instructions run directly on the CPU
    - Sensitive instructions cause the CPU to throw an exception to the OS

“Classic” VM (Popek & Goldberg, 1974) (1/4)

- Essentials of a Virtual Machine Monitor (VMM)
  - An efficient, isolated duplicate of the real machine.
  - **Equivalence**
    - Software on the VMM executes identically to its execution on hardware, barring timing effects.

      i.e. Running on VMM == Running directly on HW



  - **Performance**
    - Non –Privileged instructions can be executed directly by the real processor, with no software intervention by the VMM.

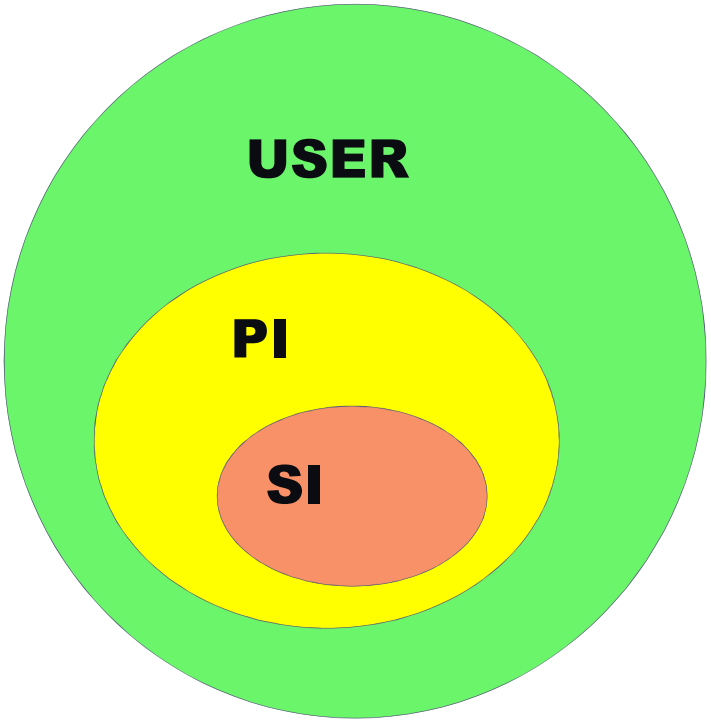
      i.e. Performance on VMM == Performance on HW
  - **Resource control**
    - The VMM must have complete control of the virtualized resources.

“Classic” VM (Popek & Goldberg, 1974) (2/4)

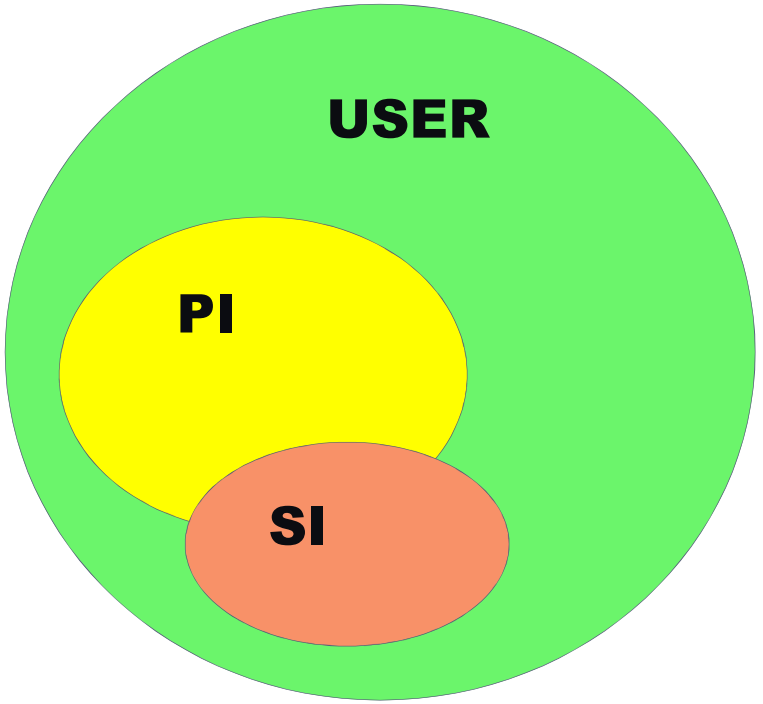
- Instruction types
  - Privileged instructions: generate trap when executed in any but the most-privileged level
    - Execute in privileged mode, trap in user mode
    - E.g. x86 LIDT : load interrupt descriptor table address
  - Privileged state: determines resource allocation
    - Privilege mode, addressing context, exception vectors, …
  - Sensitive instructions: instructions whose behavior depends on the current privilege level, or modify H/W state
    - Control sensitive: change privileged state
    - Behavior sensitive: exposes privileged state
    - E.g. x86 POPF : pop stack to EFLAGS (in user-mode, the ‘interrupt enable’ bit is not over-written)

“Classic” VM (Popek & Goldberg, 1974) (3/4)

Theorem 1: A VMM may be constructed if the set of SI’s is a subset of the set of PI’s



ISA is Virtualizable



ISA is NOT Virtualizable

“Classic” VM (Popek & Goldberg, 1974) (4/4)

- To build a VMM, it is sufficient for all instructions that affect the correct functioning of the VMM (SI’s) always trap and pass control to the VMM.
  - This guarantees the “resource control property”
  - Non-privileged instructions are executed without VMM intervention
  - Equivalence property: We are not changing the original code, so the output will be the same.

Mostly-virtualizable Architectures ☹

- x86
  - Sensitive push/pop instructions are not privileged
  - Segment and interrupt descriptor tables in virtual memory
- Itanium
  - Interrupt vectors table in virtual memory
- MIPS
  - User-accessible kernel registers k0, k1 (save/restore state)
- ARM
  - PC is a general-purpose register
  - Exception returns to PC (no trap)

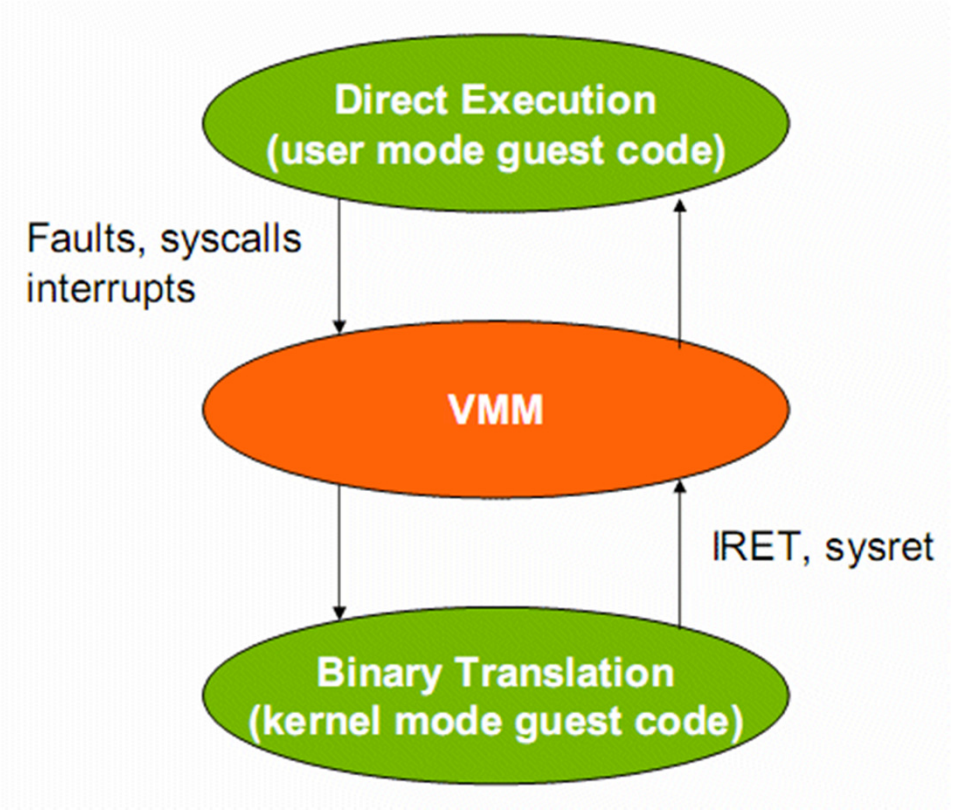
Virtualization overheads

- VMM maintains virtualized privileged machine state
  - Processor status, addressing context, device state, …
- VMM emulates privileged instructions
  - Translation between virtual and real privileged state
    - E.g. guest-to-real page tables
- Traps are expensive
  - Several 100s cycles (for x86)
- Certain important OS operations involve several traps
  - Interrupt enable/disable for mutual exclusion
  - Page table setup/updates for fork()

How to achieve safe –and- fast virtualization?

- Emulation
  - Interpret each instruction
- Paravirtualize
  - Modify the guest OS to avoid non-virtualizable instructions
- Binary translation (instead of trap-and-emulate)
  - Static vs Dynamic
- Change processor architecture
  - Intel VT , AMD Pacifica → extend x86 to make "Classic Virtualization" possible [VM/370 origins !]
  - Add a new CPU mode to distinguish VMM from guest/app

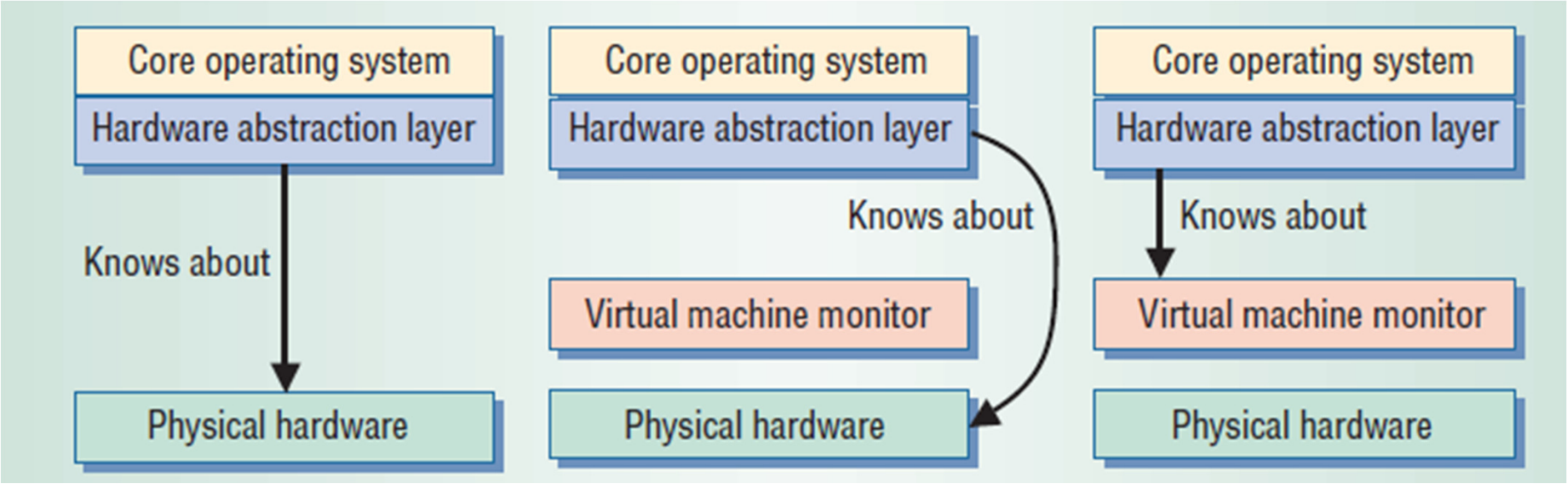
Binary Translation



+ translator cache
+ trace cache

- User applications are not translated, but run directly.
- Binary Translation only happens when the guest OS kernel gets called.

VMM architectures

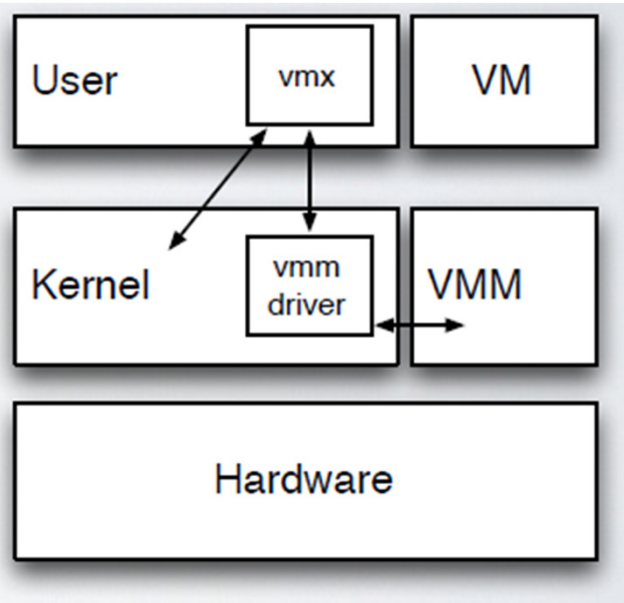


Only OS knows about H/W **Unmodified view of H/W** **Modified view of H/W**

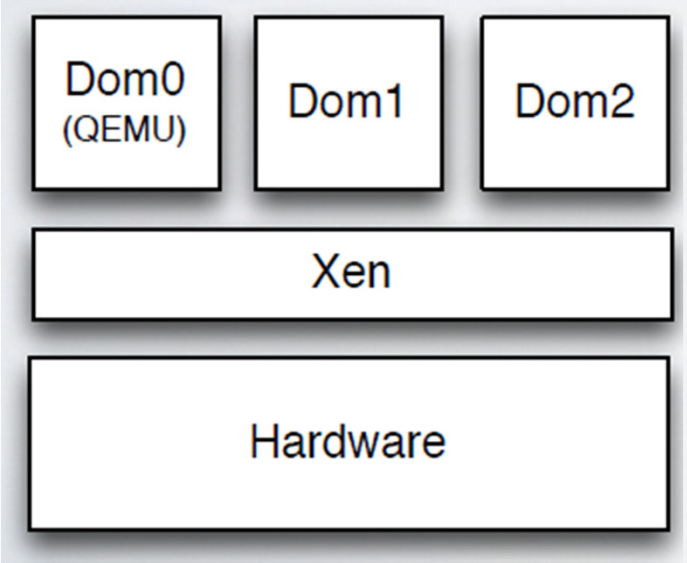
Paravirtualized VMM

VMM provides a virtual HW/SW interface to guest OSs by trapping and emulating sensitive instructions

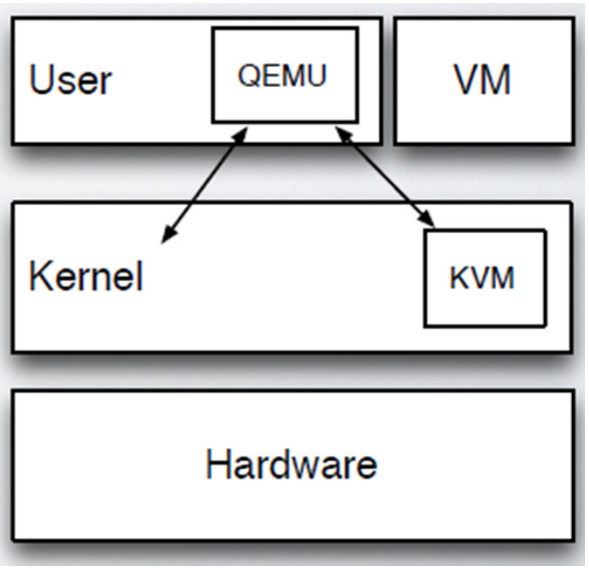
VMM examples



VMware workstation

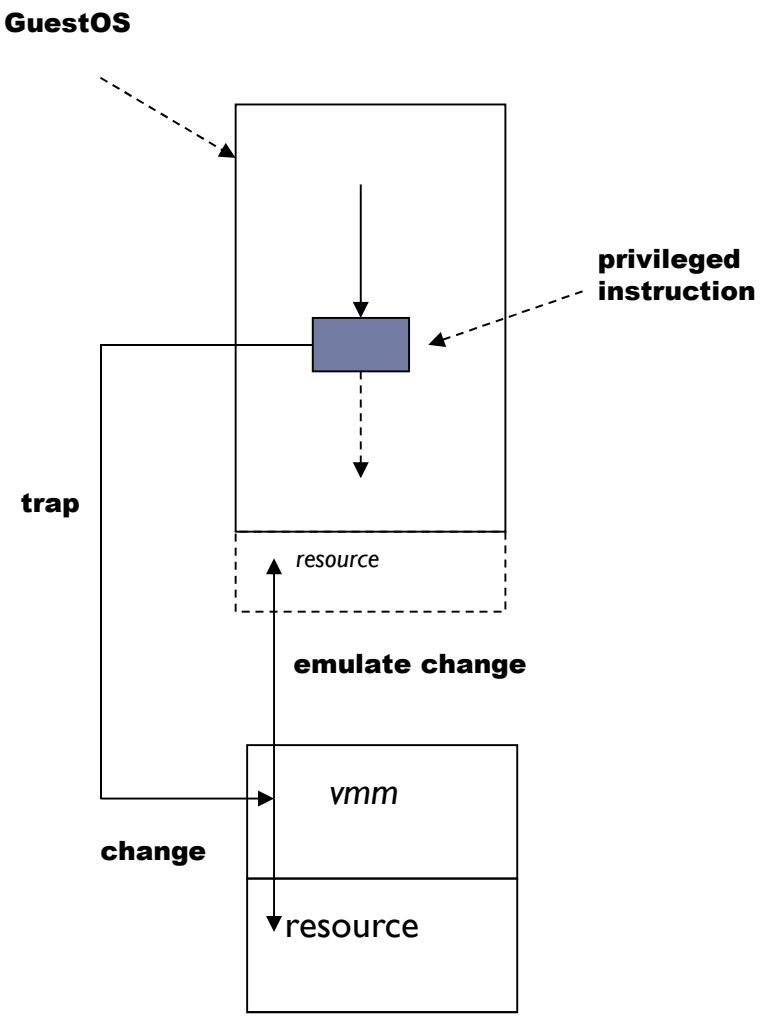


Xen



kvm

Key Techniques (1/3): De-privileging

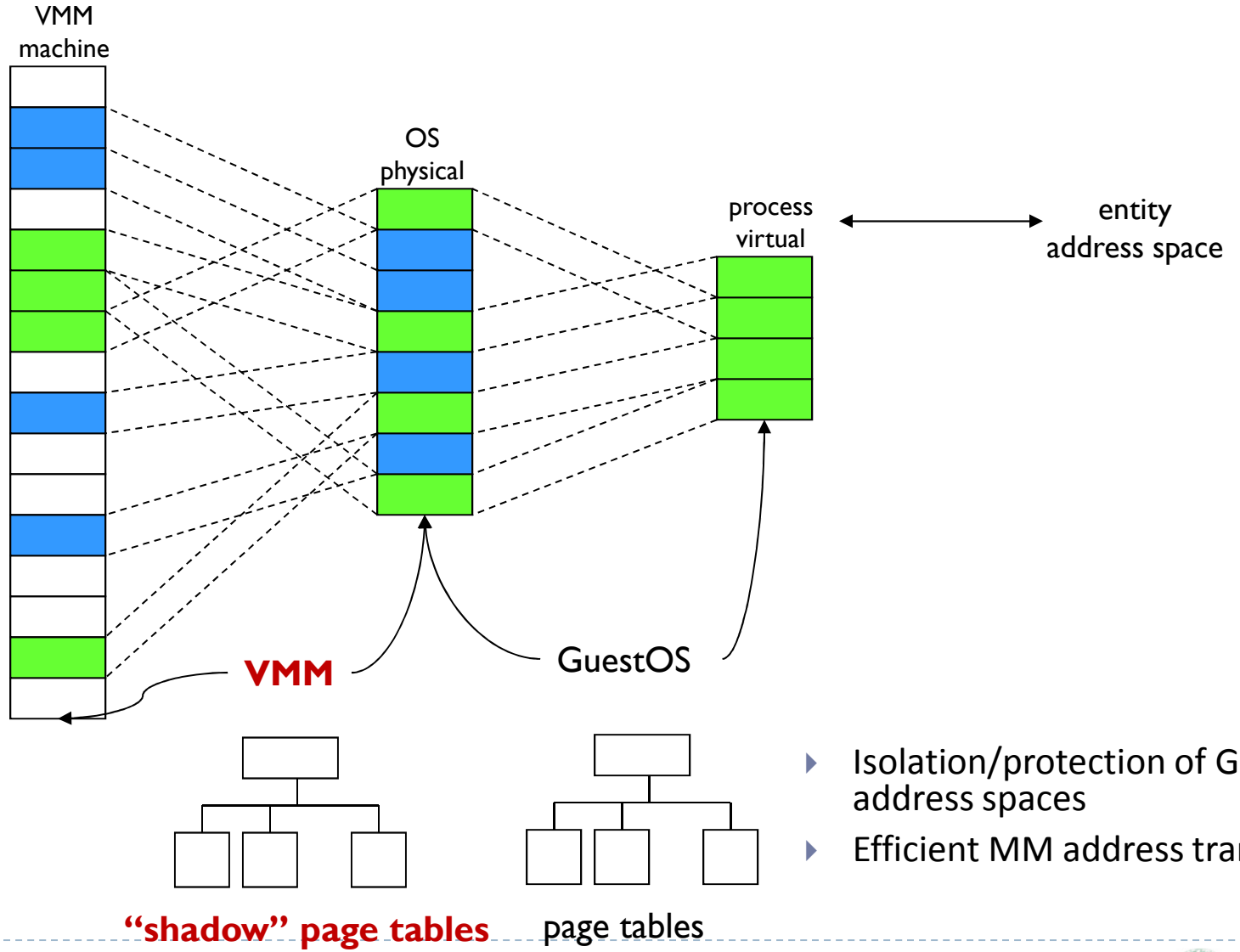


- VMM emulates the effect on system/hardware resources of privileged instructions whose execution traps into the VMM
  - aka **trap-and-emulate**
- Typically achieved by running GuestOS at a lower hardware priority level than the VMM
  - "Normal" instructions run directly on processor
  - "Privileged" instructions trap into VMM (for safe emulation)
- Problematic on architectures where privileged instructions do not trap when executed at deprivileged priority!

Key Techniques (2/3): Primary vs Shadow Structures

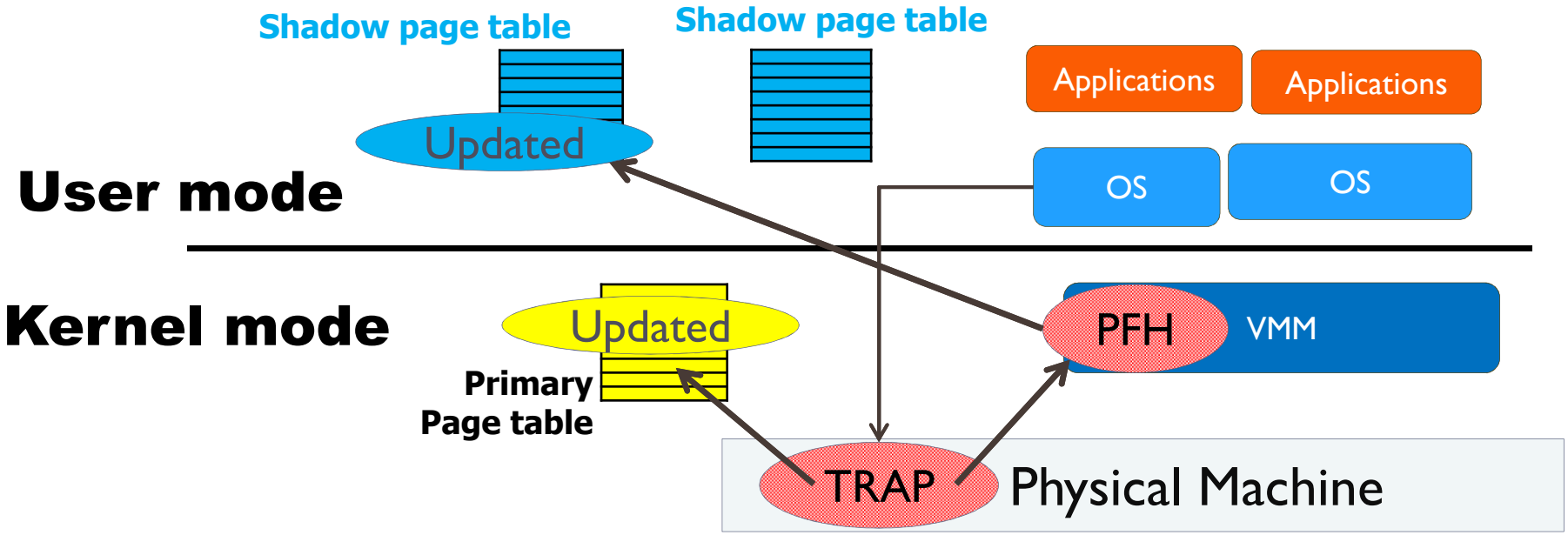
- VMM maintains “shadow” copies of critical structures whose “primary” versions are manipulated by GuestOS
  - e.g., page tables
- Primary copies needed to insure correct environment visible to GuestOS

Memory Management by the VMM



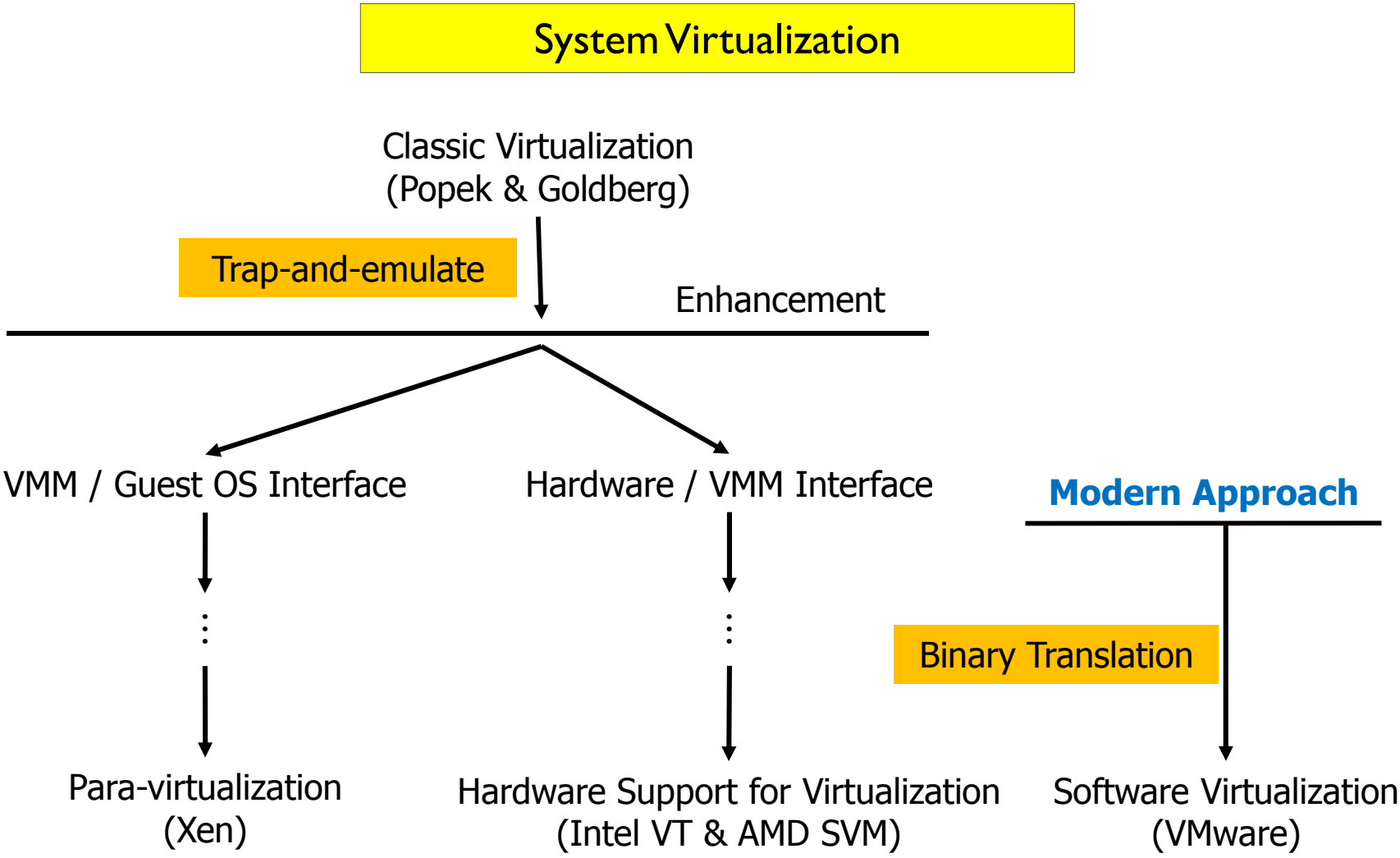
- Isolation/protection of Guest OS address spaces
- Efficient MM address translation

Key Techniques (3/3): Memory Tracing (Trace faults)



- Control access to memory so that the shadow and primary structures remain coherent
  - Write-protect primary structure so that update operations cause page faults → caught, interpreted, emulated by the VMM
  - VMM typically use hardware page protection mechanisms to trap accesses to in-memory primary structures

Evolution of System Virtualization



Sources

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- A. Whitaker, R.S. Cox, M. Shaw, S.D. Gribble, **Rethinking the Design of Virtual Machine Monitors**, IEEE Computer, vol.38, no.5, May 2005.
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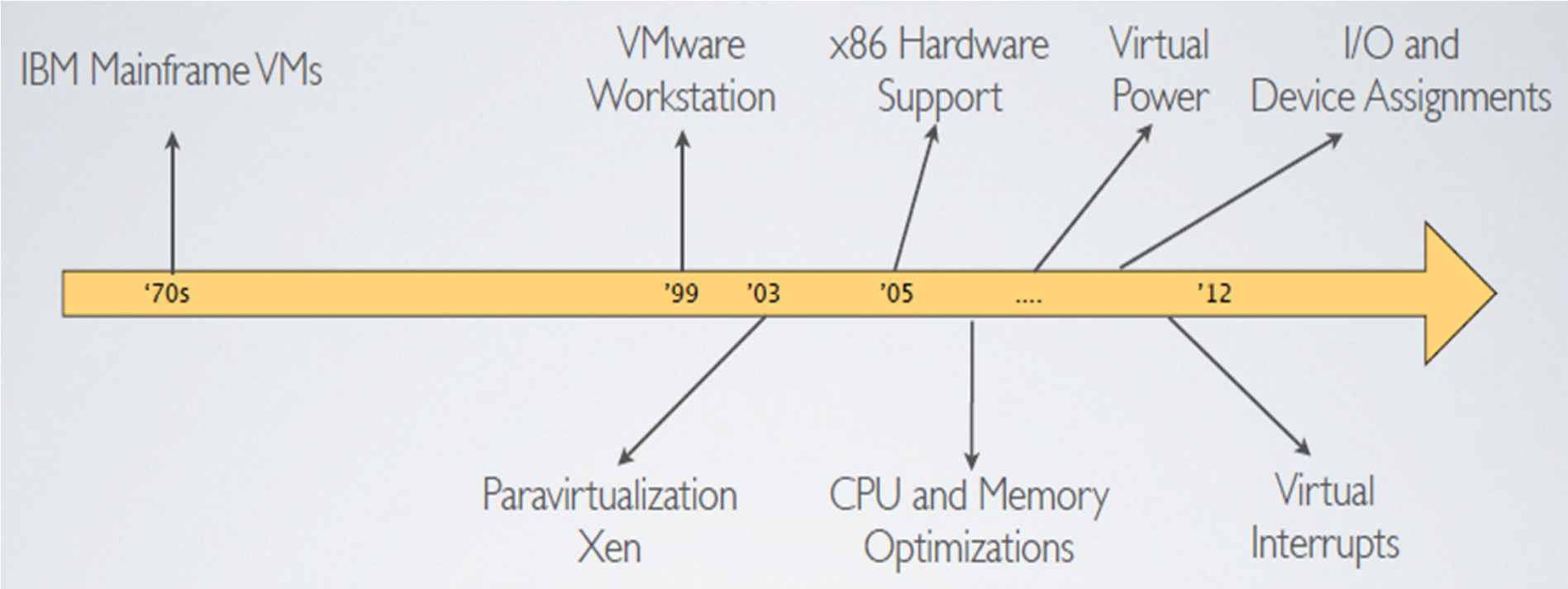
- G.J. Popek, and R.P. Goldberg, **Formal Requirements for Virtualizable Third Generation Architectures**, CACM, vol. 17 no. 7, 1974.
- Jim Smith and Ravi Nair, **Virtual Machines: Versatile Platforms for Systems and Processes**, ISBN-10: 1558609105, Elsevier, 2005

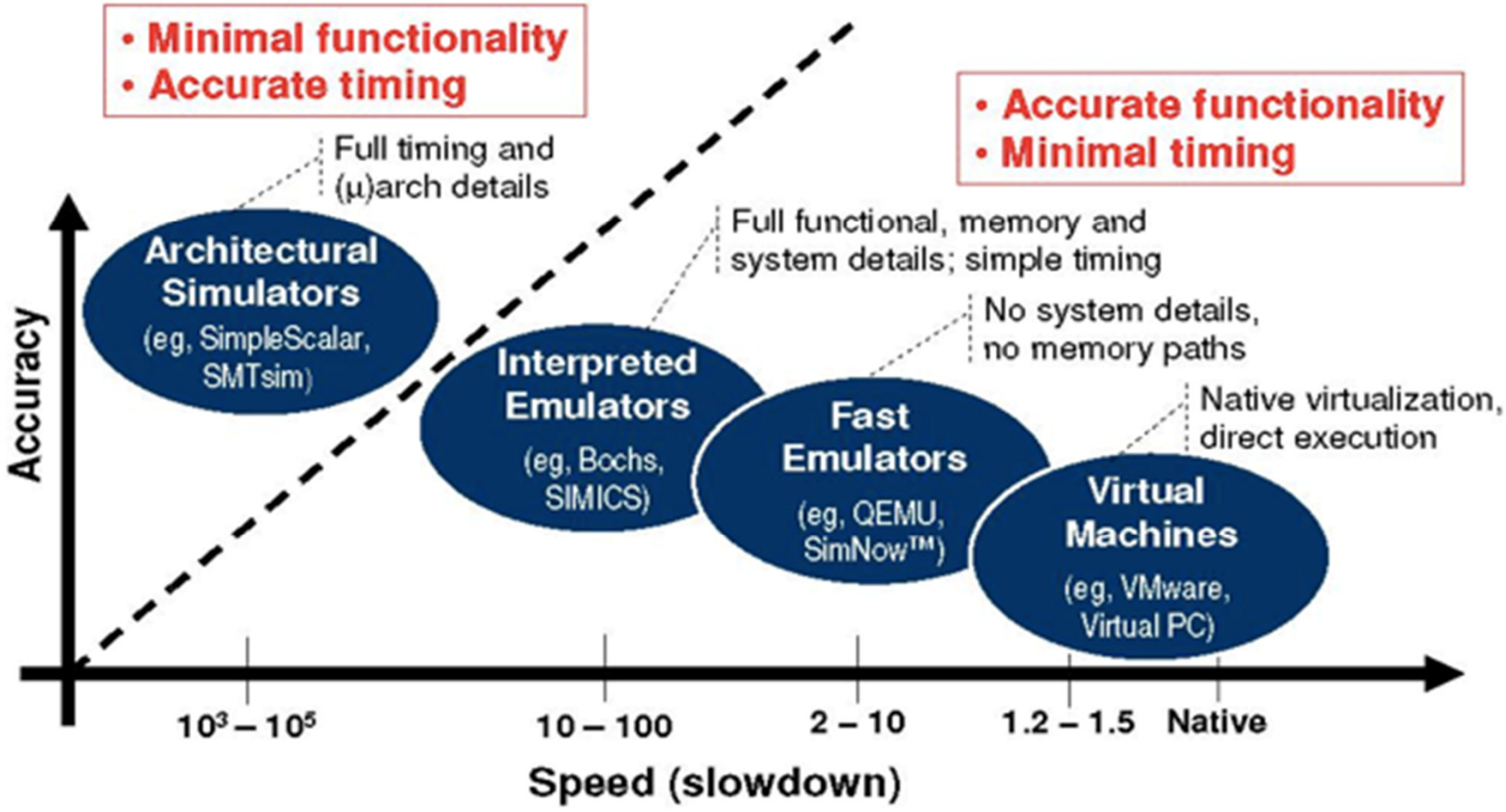
Virtualization Timeline (C. Dall – 2013)



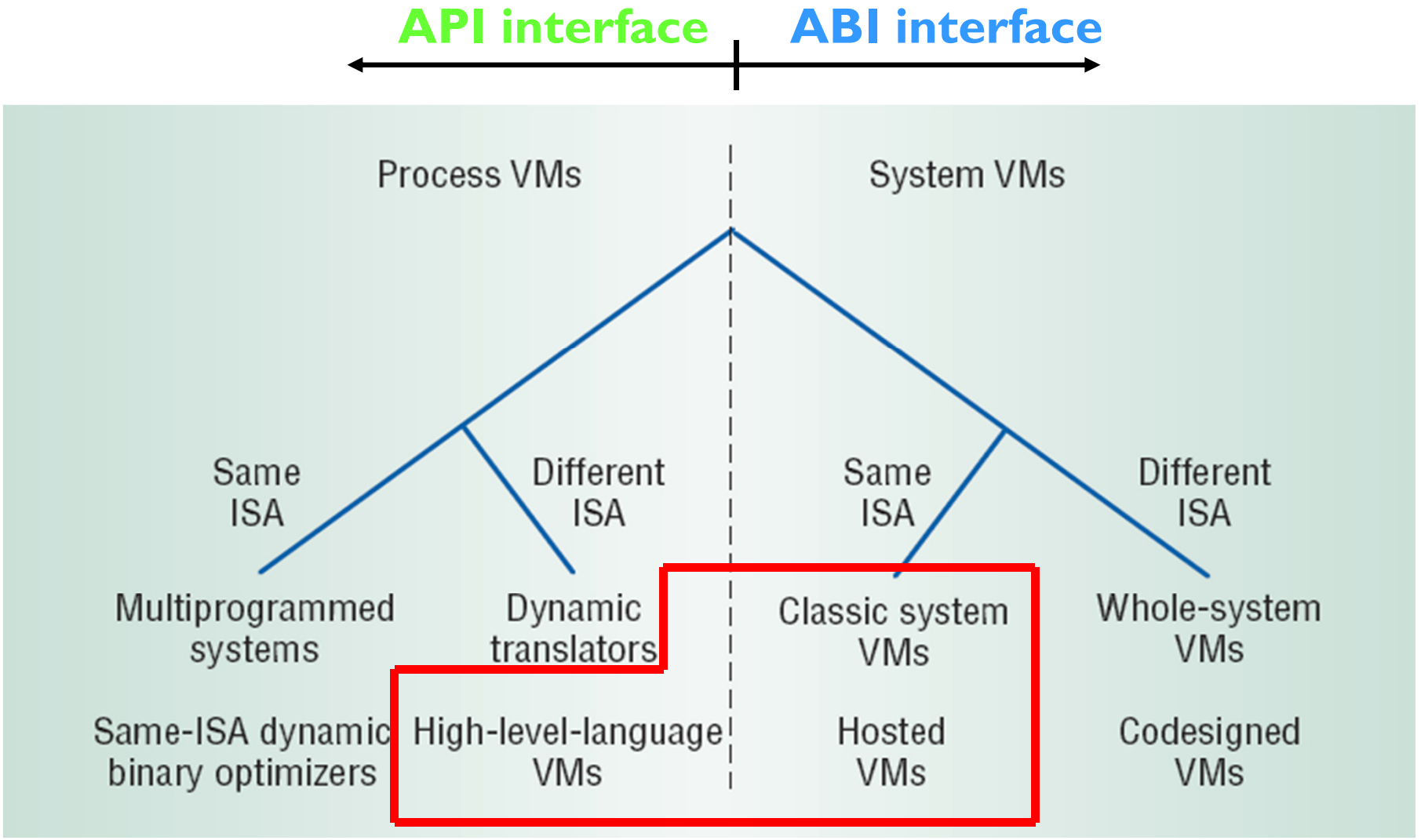
Virtual machines were popular in 60s-70s → IBM OS/370

- Share resources of mainframe computers to run multiple single-user OSs
- Interest is lost by 80s-90s: development of multi-user OS, rapid drop in H/W cost
- Hardware support for virtualization is "lost" … until the late 90s (VMware)

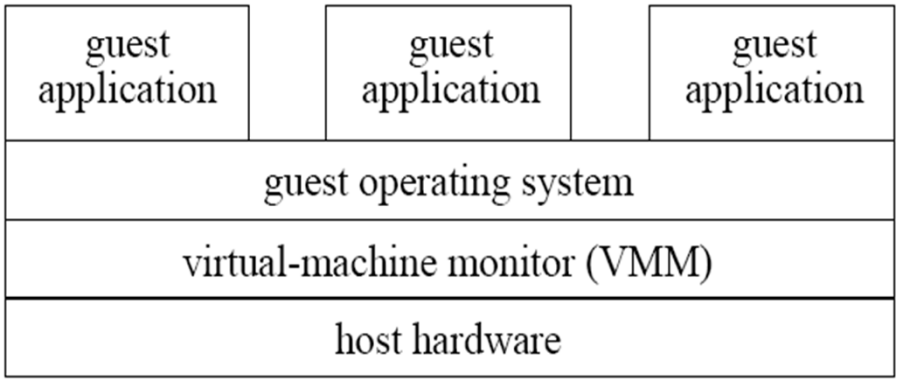
Virtualization alternatives & their performance



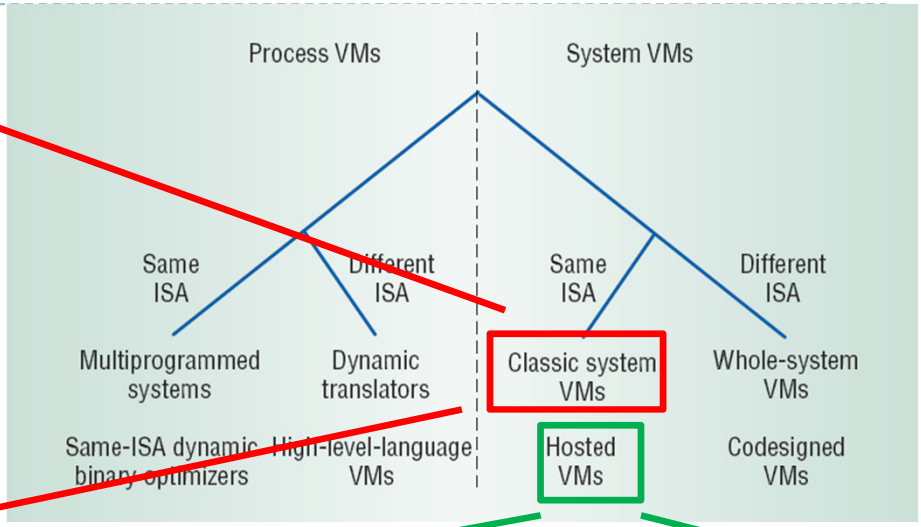
Design space



System VMMs



Type 1

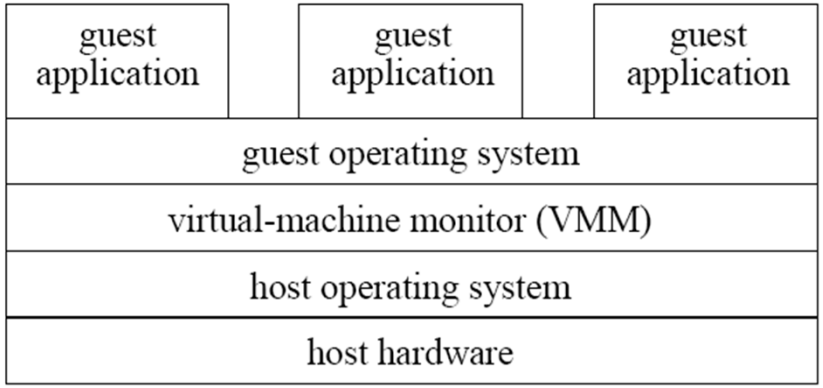


Type 1: runs directly on hardware

- primary goal: performance
- Examples: OS/370, VMware ESXi

Type 2: runs on host OS

- primary goal: ease of installation
- Example: User-Mode Linux, VMware Workstation

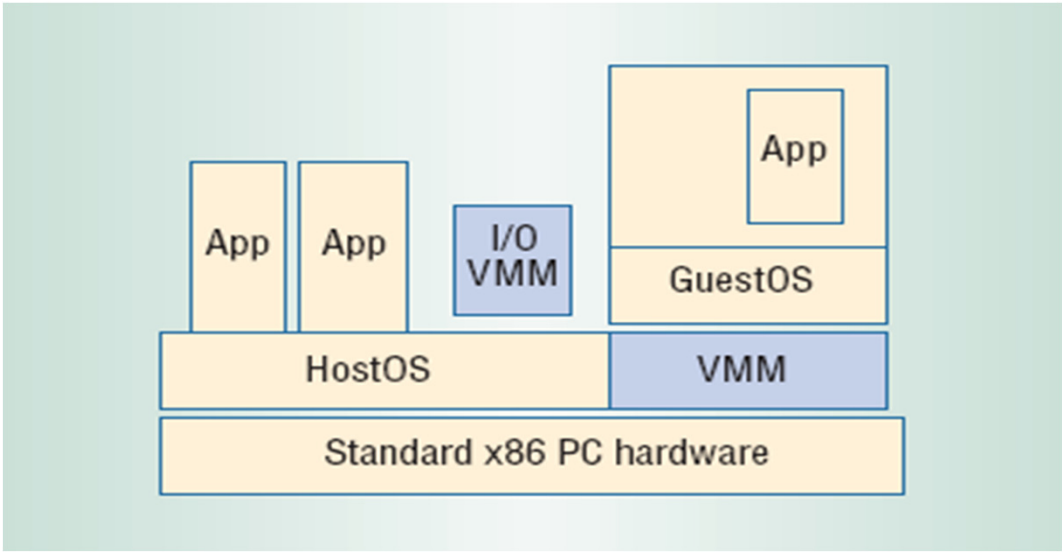


Type 2

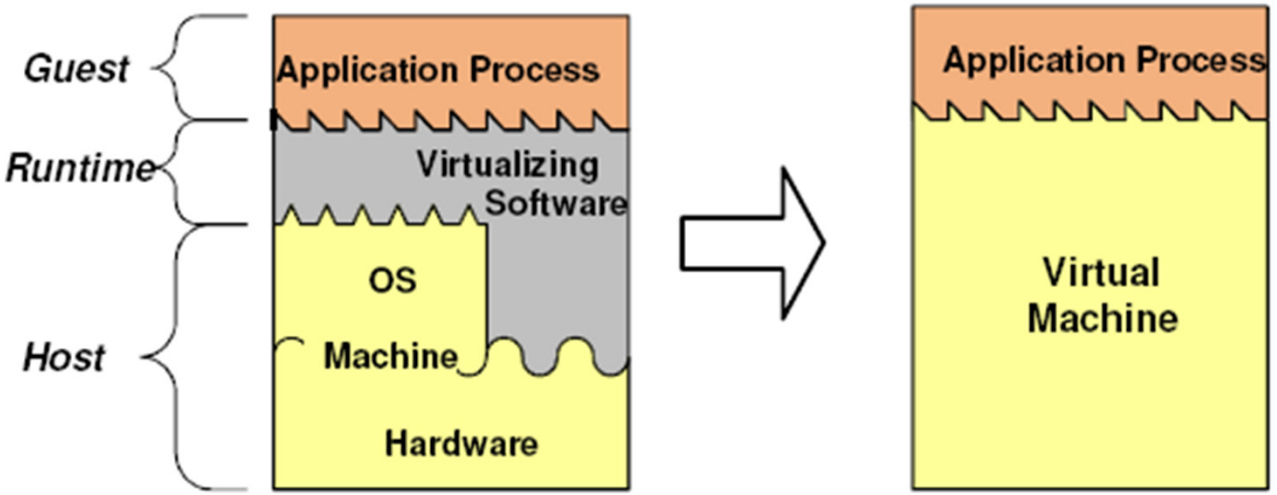
Hosted VMMs

- Hybrid between Type 1 and Type 2
  - "Core VMM" runs directly on hardware
    - Improved performance as compared to "pure Type 2"
    - Leverage s/w engineering investment in host OS for I/O device support
  - I/O services provided by host OS
    - Overhead for I/O operations, reduced performance isolation

Example: VMware Workstation



Process vs System VM



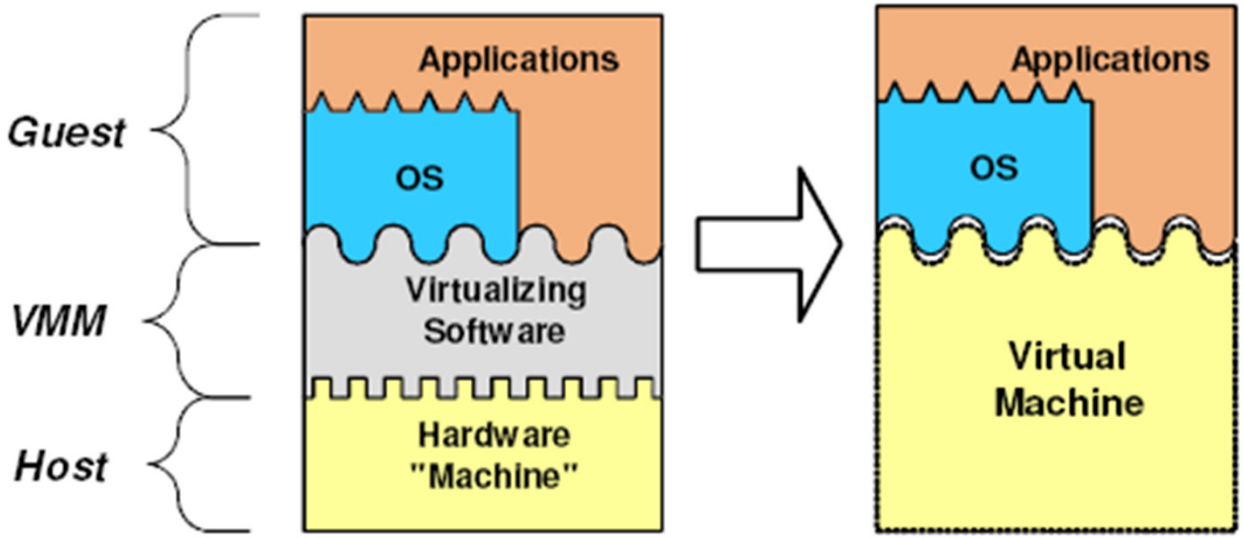
Process:

Provides API interface

+ Easier to install

+ Leverages OS services – e.g. device drivers

- Execution overhead



System:

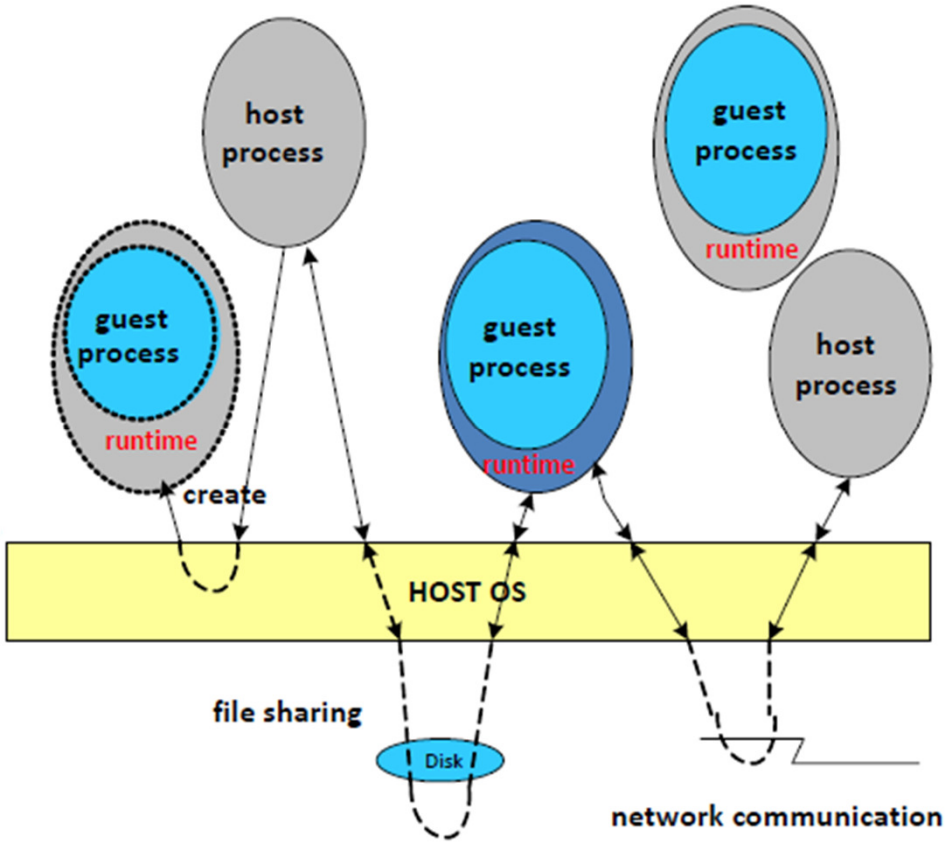
Provides ABI interface

+ Efficient execution

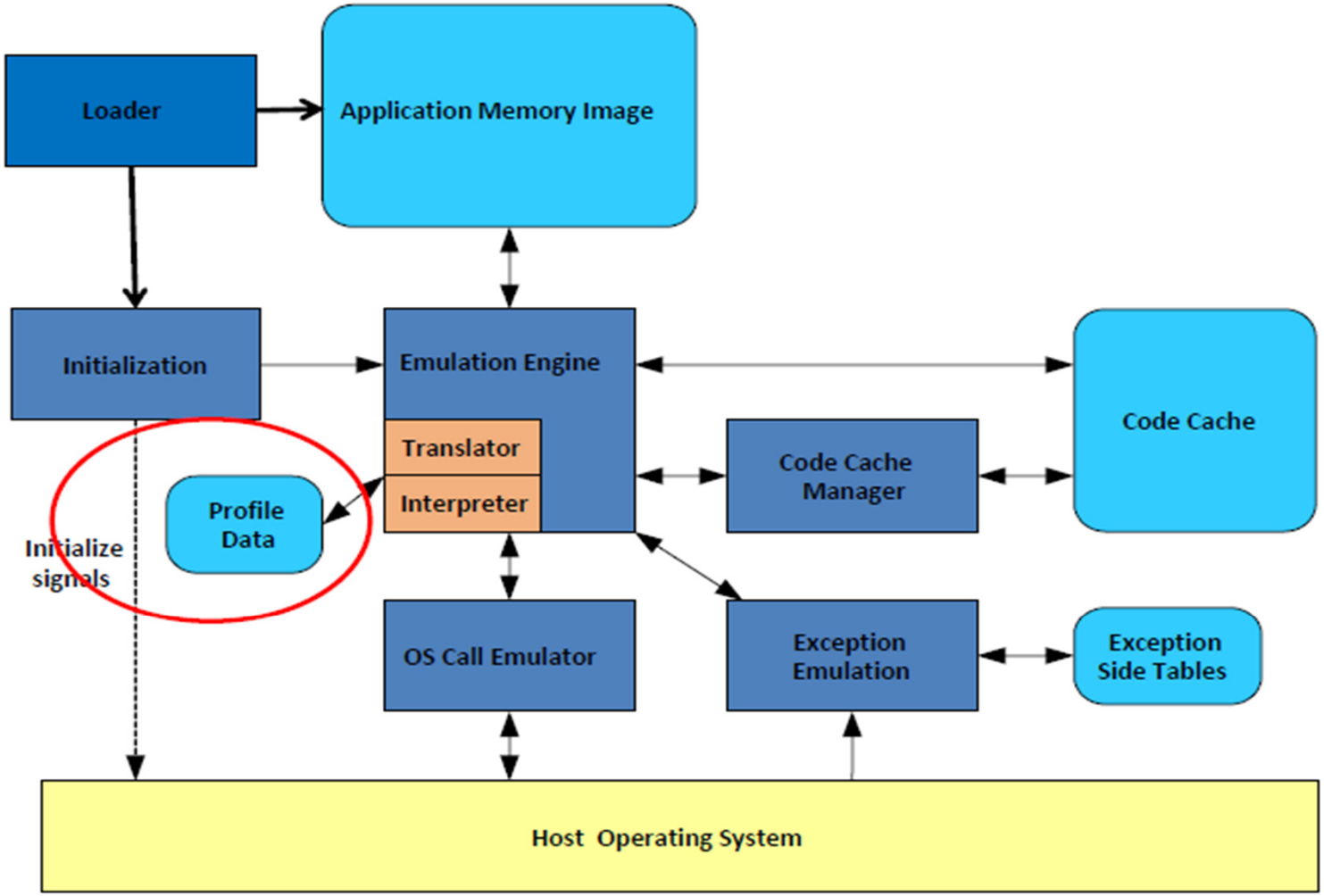
+ Can add OS-independent services – e.g. migration, checkpointing, sandbox

Process VM concept

- A guest program developed for a machine (ISA and OS) other than the user's host system can be used in the same way as all other programs in the host system
- **Runtime system**
  - Encapsulates an individual guest process giving it the same appearance as a native host process
  - All host processes appear to conform to the guest's worldview



Process VM architecture



Whole-system VMMs

- Case of GuestOS ISA != HostOS ISA
- Full emulation of GuestOS and its applications
- Example: VirtualPC

Acceleration techniques

- Binary translation
  - locate sensitive instructions in guest binary and replace on-the-fly with emulation code or hypercall
    - VMware, QEMU
- Para-virtualization
  - Port the GuestOS to modified ISA
    - Xen, L4, Denali, Hyper-V
    - Reduce number of traps
    - Remove un-virtualizable instructions
- Hardware support
  - Make all sensitive instructions privileged (!)
  - Intel VT-x, AMD SVM
    - Xen, VMware, kvm
  - Nested page tables
  - Direct device assignment, IOMMU, Virtual interrupts