Virtual Machines

- CS418, Spring2006, 17-19 April 2006

Contents

- What is a VM?
- Applications of VMs
- Classification of VM
- Implementation Issues
- Future Directions
- Virtual Machines vs Microkernels
  - Not covered

What is a machine?

- Machine is an implementation of some exported interface.
- For example:
  - Hardware
    - *Interface*: ISA+Exceptions
  - Operating System
    - *Interface*: *User-Mode* ISA + System calls
  - Programming Language
    - *Interface*: Core Language constructs

What is a Virtual Machine?

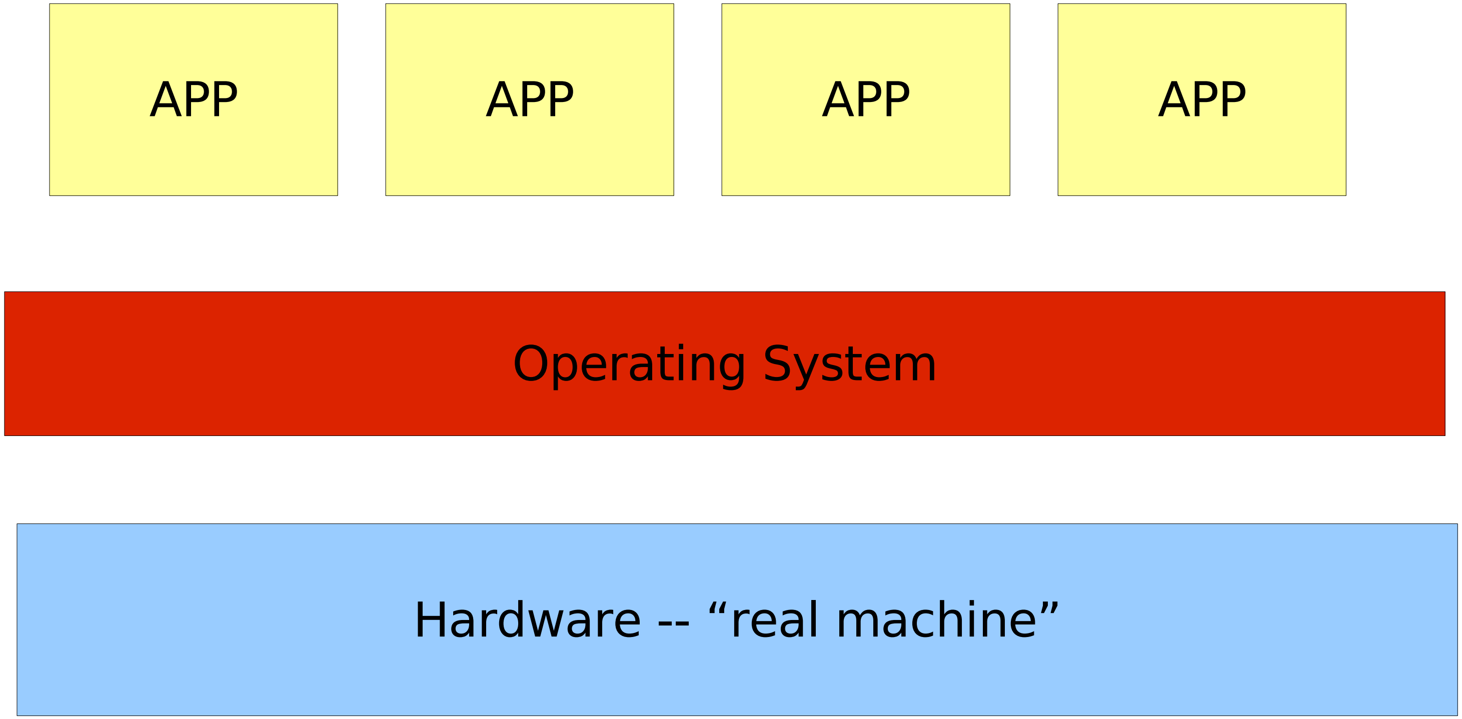
- Something that is not a machine? No
- It is a machine that provides an illusion of some other machine
- Virtual Machine Monitor (VMM) provides the same interface* as the other machine, and simulates its implementation behavior
- Interesting part: It can do useful things between the interface and the implementation that not usually observable by the users (guests).

(*) in some cases, very similar interface with a little modifications

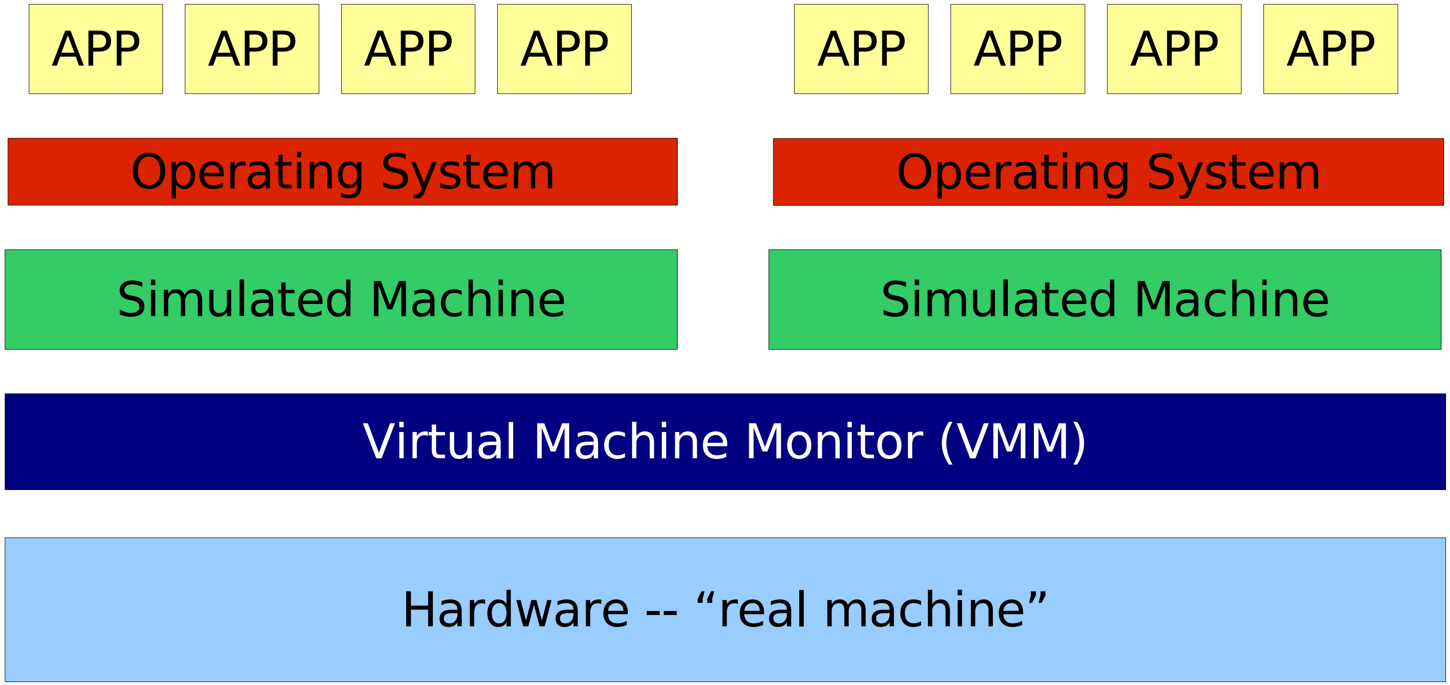
Types of Virtual Machines

- Kind 1: Full Machine Virtualization
  - *Type I*: The VMM runs on bare hardware. All guest operating systems run within the control of the VMM.
  - *Type II*: The VMM runs as an ordinary application inside some host operating system, but emulates a machine that can run one or more OS-es within it.
- Kind 2: Paravirtualization
  - *Type III*: The VMM runs on bare hardware, but does not emulate it precisely. The guest OS-es that run on this VMM must adapt to the new interface.
- Kind 3: Language Runtimes
  - Ex: Java Virtual Machine (Not to be covered)

Normal Setup



Virtual machine Type I



Motivation

- Machines are (or were) expensive
- Can run more than one OS
- Can “clone” a machine for backup
- Planning for fail-over
- Mass deployment (e.g. Web servers)
- Upgrade and software migration
- Machine Migration and Load balancing

Motivation II

- Emulating a *different* machine (e.g. for OS bring-up or backwards compatibility)
- Providing a system-level debugging environment
- Administration and logging
- Simulation and Experimentation
  - Ex: simulating large networks.
- Strong Isolation between the guest Operating systems.

What Must Be Emulated?

- Instruction set (both user and supervisor)
- Exception handling interface
- Interrupt mechanism
- Some set of devices
- Basically, everything the OS would normally see.

IBM 360

- Provided Uniform Instruction set for a wide range of machines
- Not all machines implemented the whole ISA
- Low-end machines emulated some instructions in the terms of others.
  - (ex: multiplication through repeated addition)

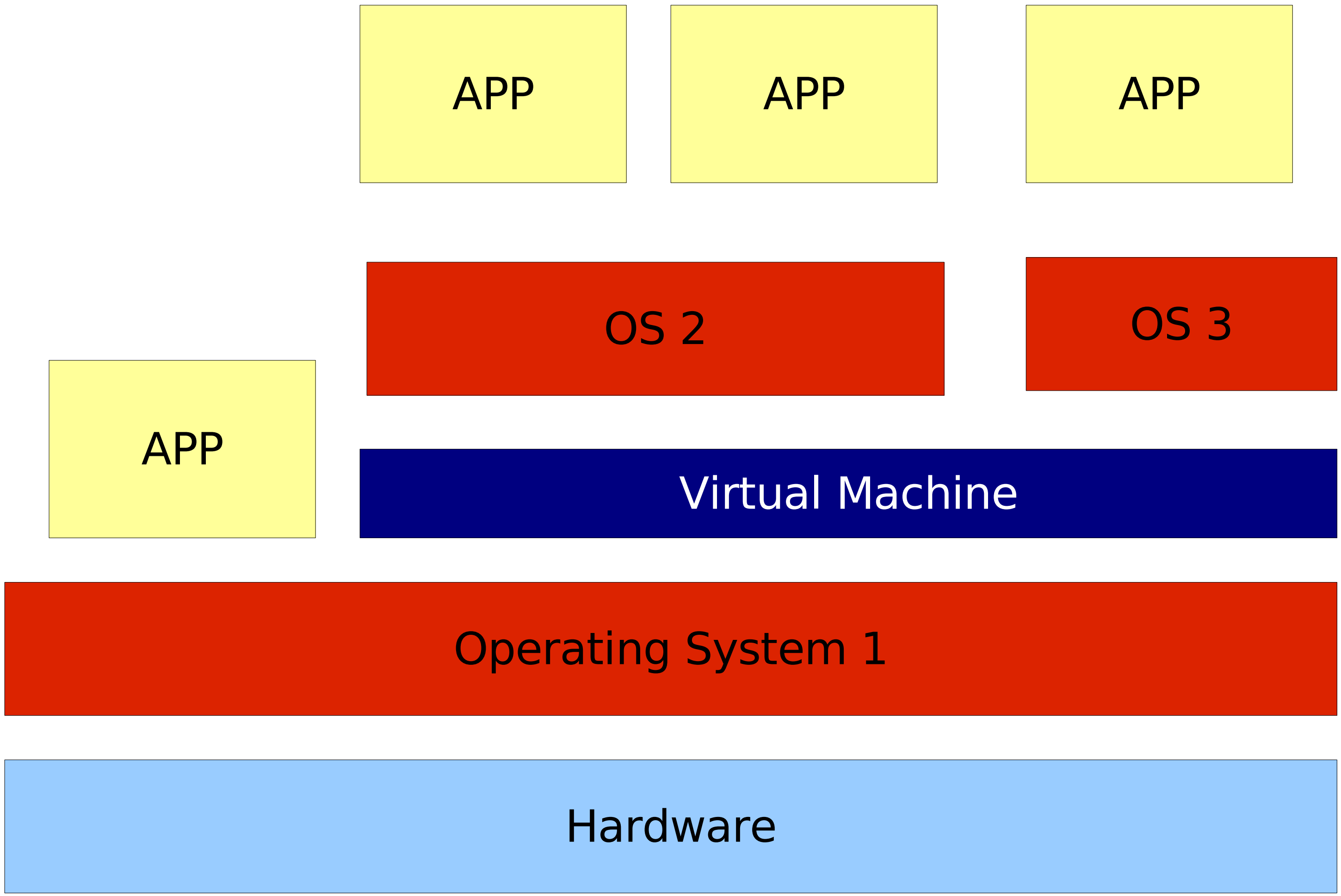
IBM 370

- Used to implement reliable multiplexing of IBM’s mainframe computers
- Each task was run in its own Virtual machine.
- Virtualizability was an explicit goal of the architecture
- Virtualization was complete: one of the things that could be run inside the VM 370 is VM 370 itself.

Virtual Machines Type II

- The VMM runs as an ordinary application inside some host operating system, but emulates a machine that can run one or more OS-es within it.
  - Ex: VMWare, QEMU, UML

Virtual Machines Type II



Motivations

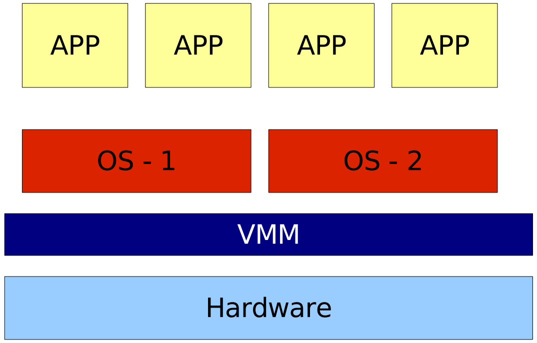
- Operating system development and debugging
  - OS development without having to run on the native machine (and damage it?)
  - Can obtain a dump if the guest-OS crashes
  - Can use the host operating system to control or debug the guest operating system
- Simpler implementation, utilizes the facilities and abstractions of the host OS of emulating the machine.

AMD SimNow

- Developed by VirtuTech for AMD
- Provides full system simulation for OS bringup.
- Earliest “deployment” of AMD Pacifica, NX, and other new features
- Lets supporting software be developed early for hardware testing and faster market deployment.

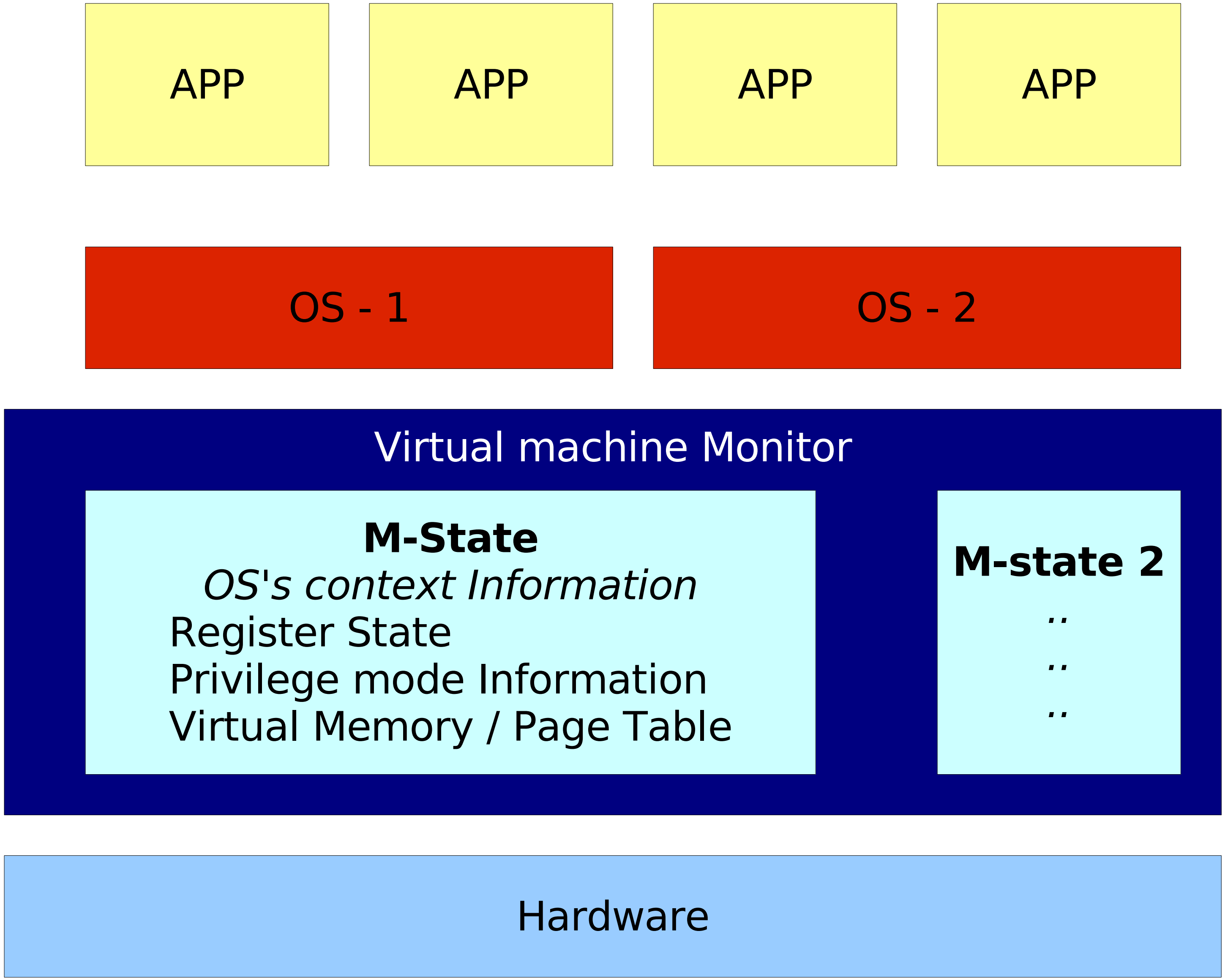
What does it take to Vitrualize a system?

- For Full Machine Virtualization:
  - CPU Virtualization
  - Memory Virtualization
  - Device (I/O) Virtualization
  - Interrupt / Exception Virtualization



- Considerations:
  - Transparency
  - Performance
  - Complexity

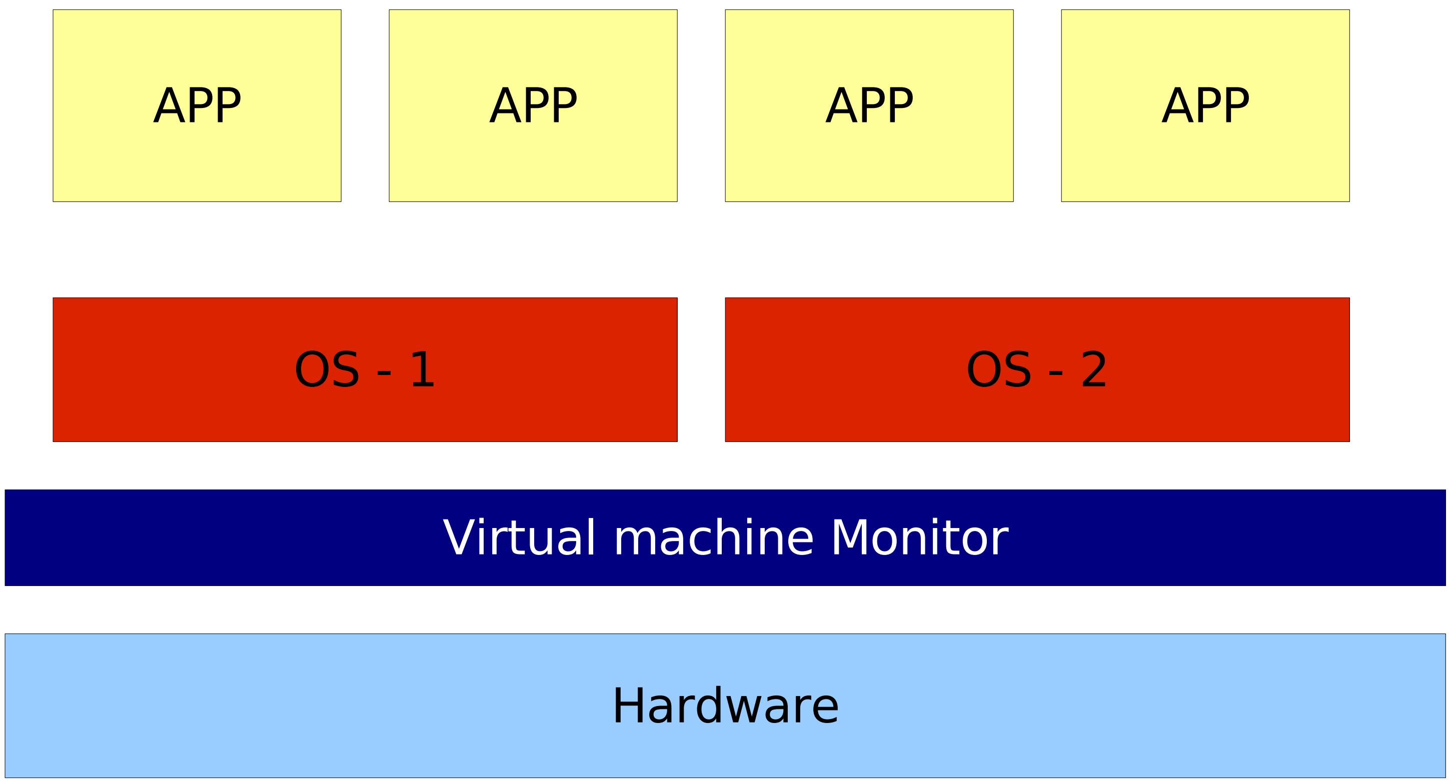
What is in the VMM ?



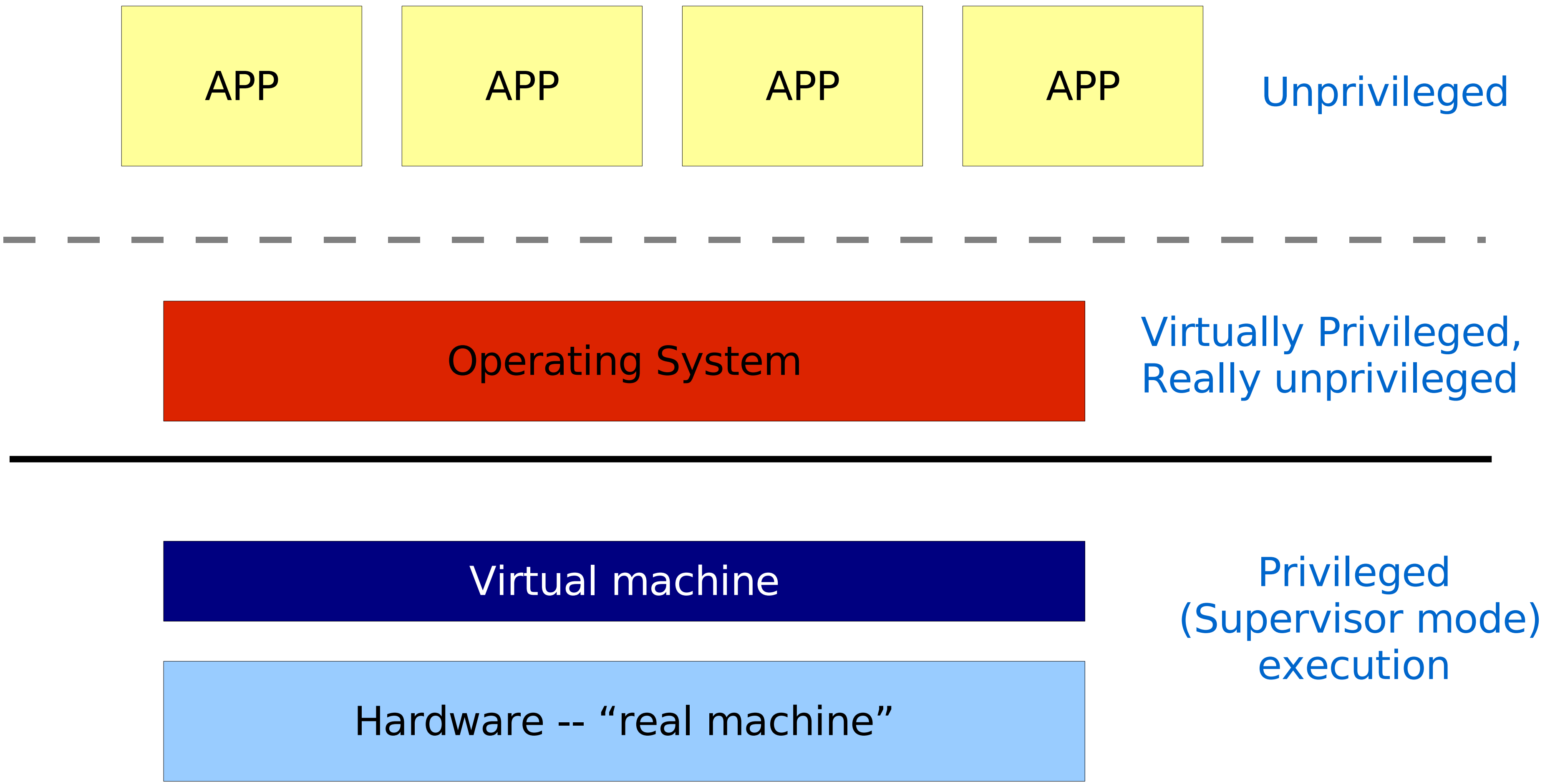
Virtualizing the instruction set

- Consider the privileged instruction

  `cli` – clear interrupt flag



Staying in Control



Is this enough?

- G. J. Popek and R. P. Goldberg. Formal requirements for virtualizable third generation architectures. In Proc. of the Fourth Symposium on Operating System Principles, Yorktown Heights, New York, Oct. 1973.
- Provide Sufficient Conditions for Vitrualizability.

Definitions

- Privileged Instructions
- Sensitive Instructions
  - Control Sensitive
  - Behavior Sensitive
    - Location Sensitive
    - Mode Sensitive
- “Innocuous” Instructions
- Traps

Popek-Goldberg Theorems

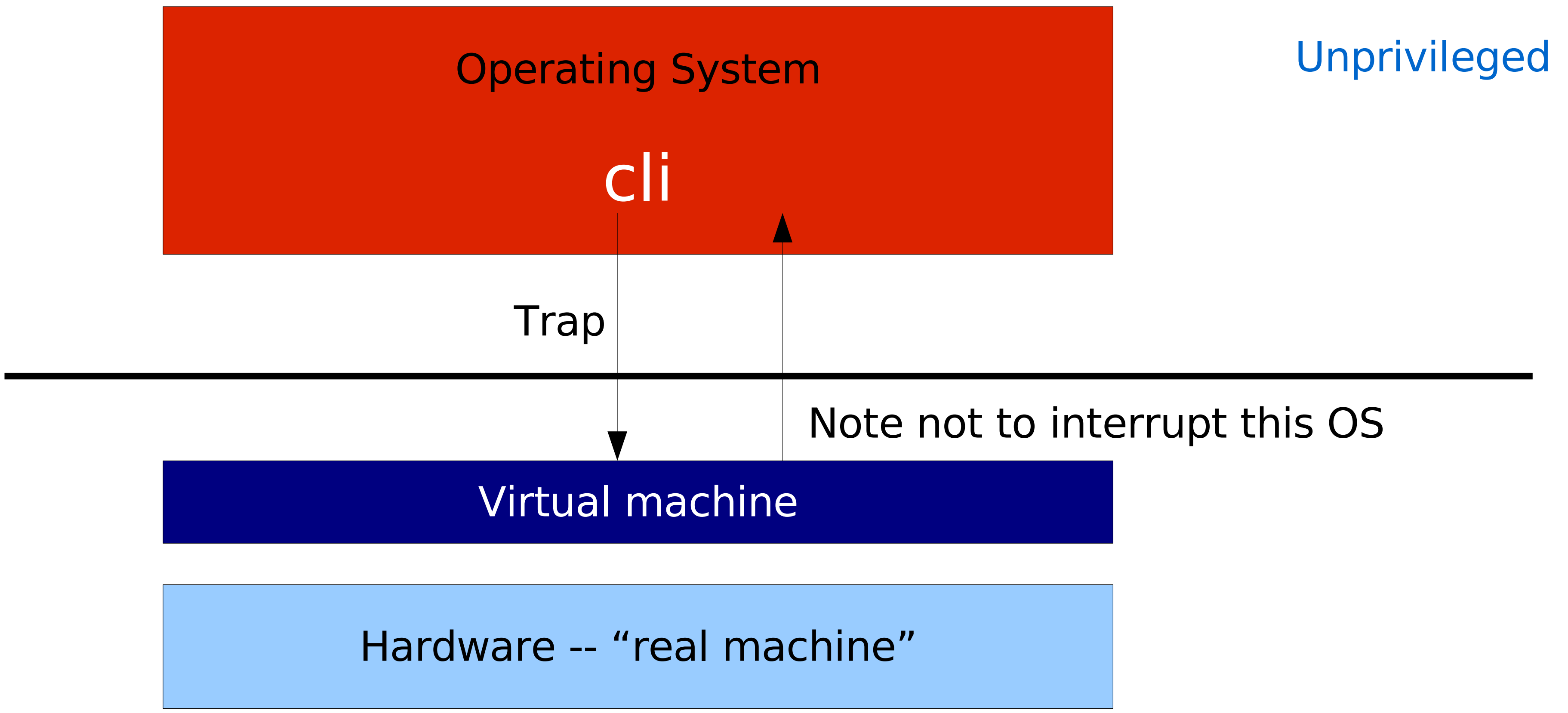
- *THEOREM 1*: For any conventional third generation computer, a virtual machine monitor may be constructed if the set of sensitive instructions for that computer is a subset of the set of privileged instructions.
- *THEOREM 2*: A conventional third generation computer is "recursively virtualizable” if it is: (a) virtualizable, and (b) a VMM without any timing dependencies can be constructed for it.
- *THEOREM 3*: A hybrid virtual machine monitor may be constructed for any conventional third generation machine in which the set of user sensitive instructions are a subset of the set of privileged instructions.

Case study - IA32

Robin, J. and Irvine, C. (2000). Analysis of the Intel Pentium' s ability to support a secure virtual machine monitor. In Proceedings of the 9th USENIX Security Symposium, Denver, Colorado, USA, August 14-17.

- Privileged Instructions
  - CLI
  - LGDT, LLDT, LIDT
  - Load/store Control Regs
  - IRET
  - HLT
  - RWMSR, WRMSR
  - RDPMC
  - LMSW
- Sensitive Instructions
  - **Pushf / Popf**
  - SGDT, SLDT, SIDT
  - SMSW
  - LAR, LSL, VERR, VERW
  - Push / Pop Segment Regs

Case 1: Privileged Instructions



The Difficult Case

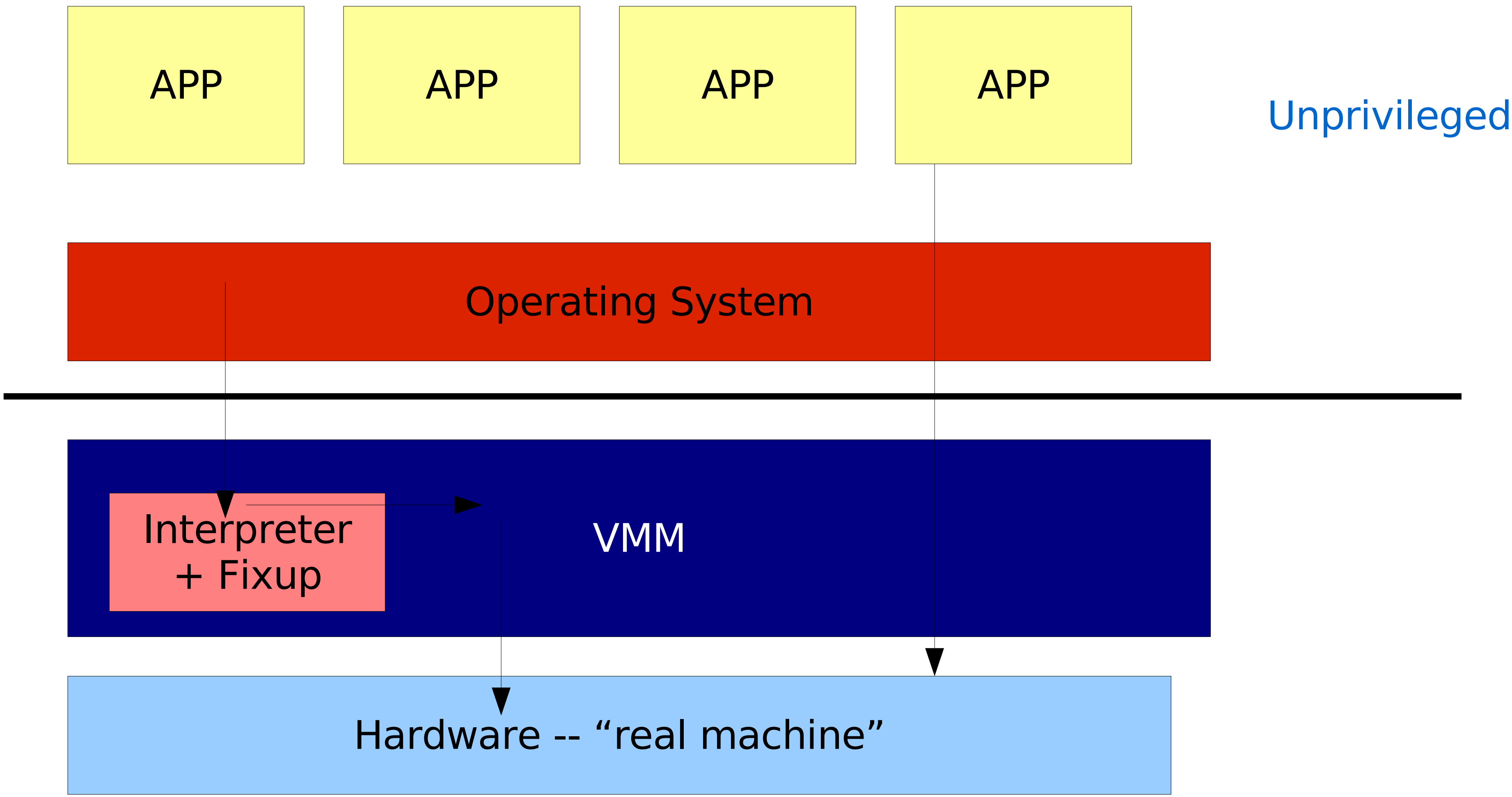
- Flags on IA32

31	22								12												0
Res	ID	VIP	VIF	AC	VM	RF	0	NT	IOPL	OF	DF	IF	TF	SF	ZF	0	AF	0	PF	1	CF

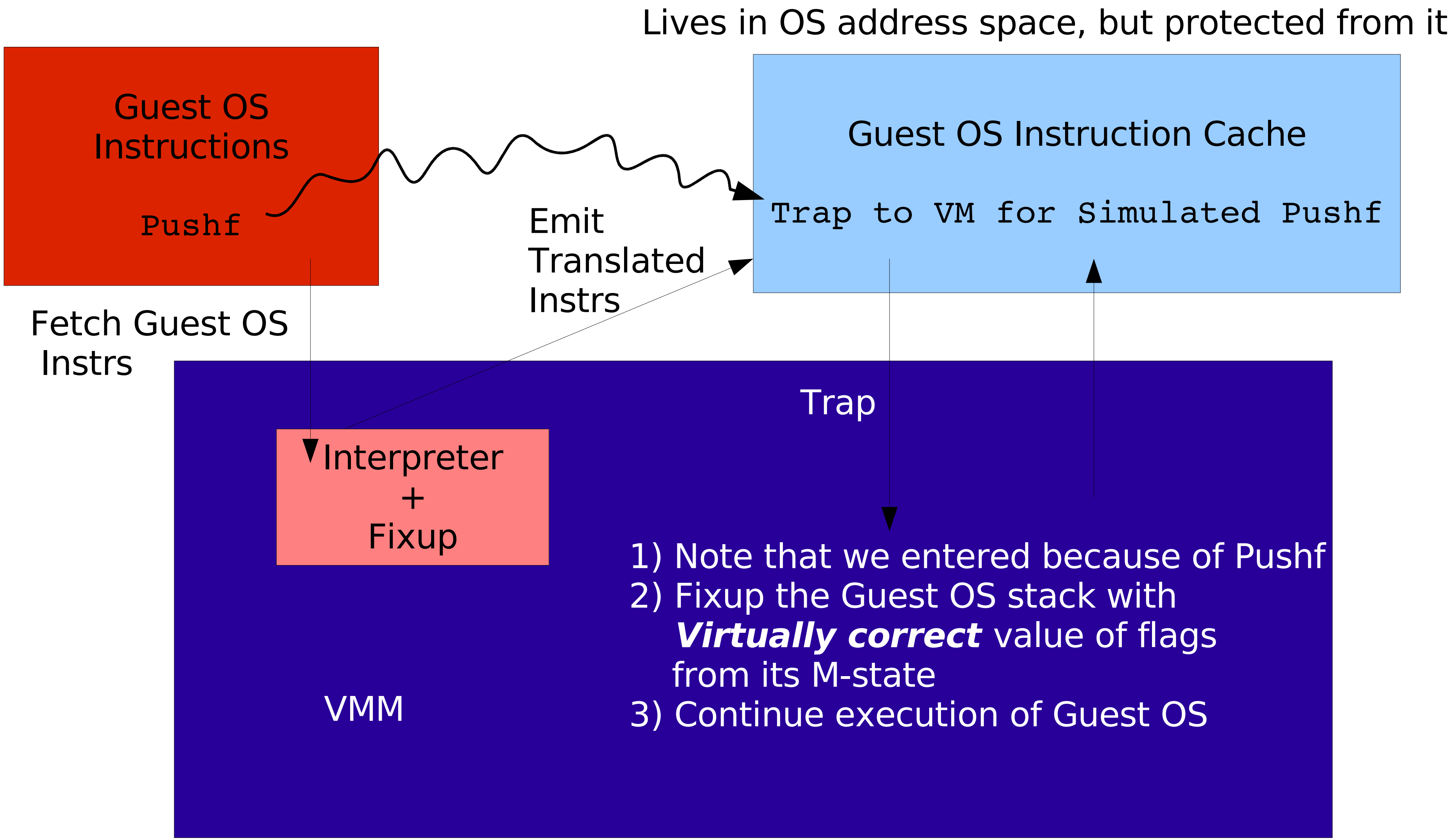
- Trying to set Privileged flags from user mode silently fails
- User mode *can read privileged flags*

Solution

- Interpret guest-OS instructions



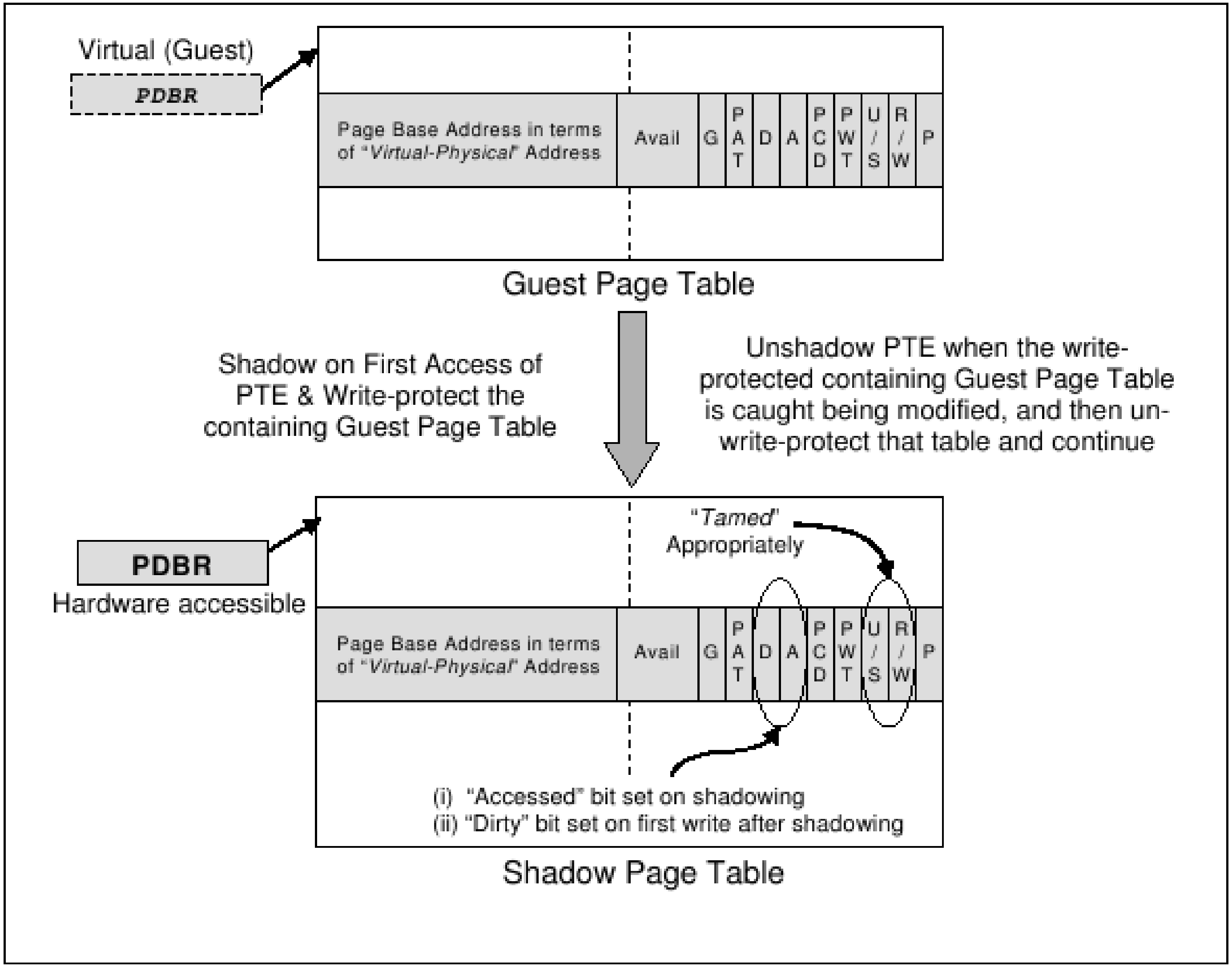
Can do a little better



MMU Virtualization

- Virtual Physical Memory
- Virtual Virtual Memory
  - Transparency: VMM cannot occupy Virtual Addresses
  - Efficiency: MMU cannot be implemented in software
  - Solution: Shadow Paging

Shadow Paging



Memory resource Management

C. A. Waldspurger. Memory resource management in VMware ESX server. In Proceedings of the 5th Symposium on Operating Systems Design and Implementation, pages 181--194, December 2002.

- Ballooning
  - Guest VM is in the best position to decide what is valuable to it
- Content based page sharing
- Hot I/O re-mapping

I/O Virtualization

- Problem: Lots of devices
  - Vendor specific interfaces
- The VMM must support all devices, but can export a uniform virtual device to all guest operating systems.
- Need to intercept Bus probes so that one OS does not take control of any device
- Isolation
  - Need to protect each VM from interfering with the other's use of the device
- Real time requirements
  - Audio, video, Network

I/O Virtualization

- Performance Issues:
  - Allow as much direct communication as possible.
  - Copying data is expensive (Network)
- Disk Virtualization
  - Every guest implements its own disk scheduling, which may interfere with one another.
- Legacy devices
  - Some PCI devices are very hard to virtualize
- Many BIOS calls Non-reentrant
- DMA
  - This circumvents virtual memory
  - Impossible to virtualize without HW support

Implementation of Type II VMs

- VMM works by mapping guest OS abstractions into HW abstractions
  - Use host OS's process abstraction for each VM
    - Use guest OS's context switching mechanism
    - Use *Ptrace* like facility for controlling these VMs
  - Use host Signals for virtual interrupts / exceptions
  - Use host's Per-process address space mappings for Virtual MMU
  - Use host provided files and devices for virtual devices where possible
    - A large file to implement a virtual “disk”
    - File read/write for virtual disk read/write

I/O Virtualization in Type II VMs

J. Sugerman, G. Venkitachalam, and B.-H. Lim, "Virtualizing I/O devices on VMWare workstation 's hosted virtual machine monitor," in Proceedings June 2001.

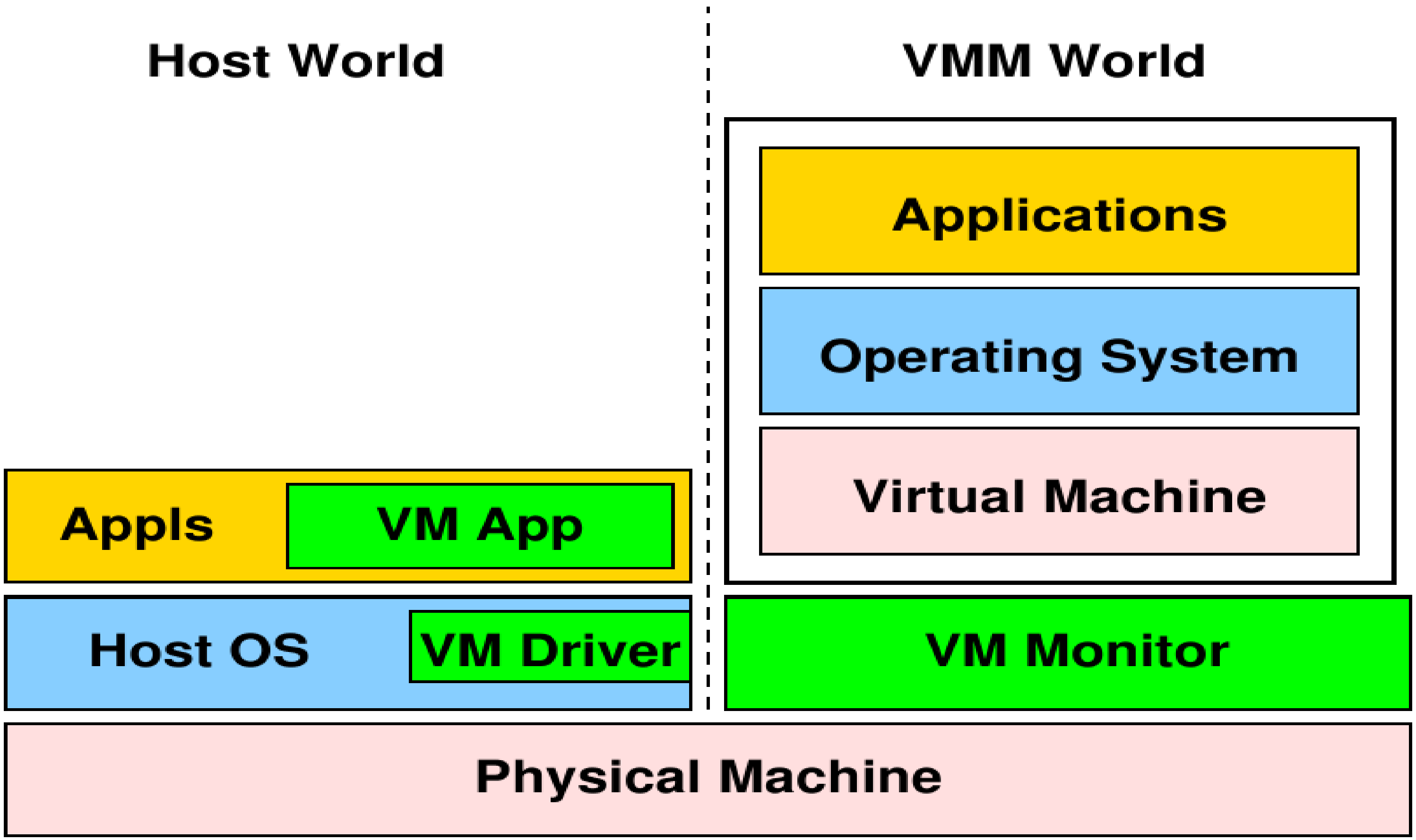


Figure adapted from the above paper.

Interrupt / Exception handling

This is not to be covered

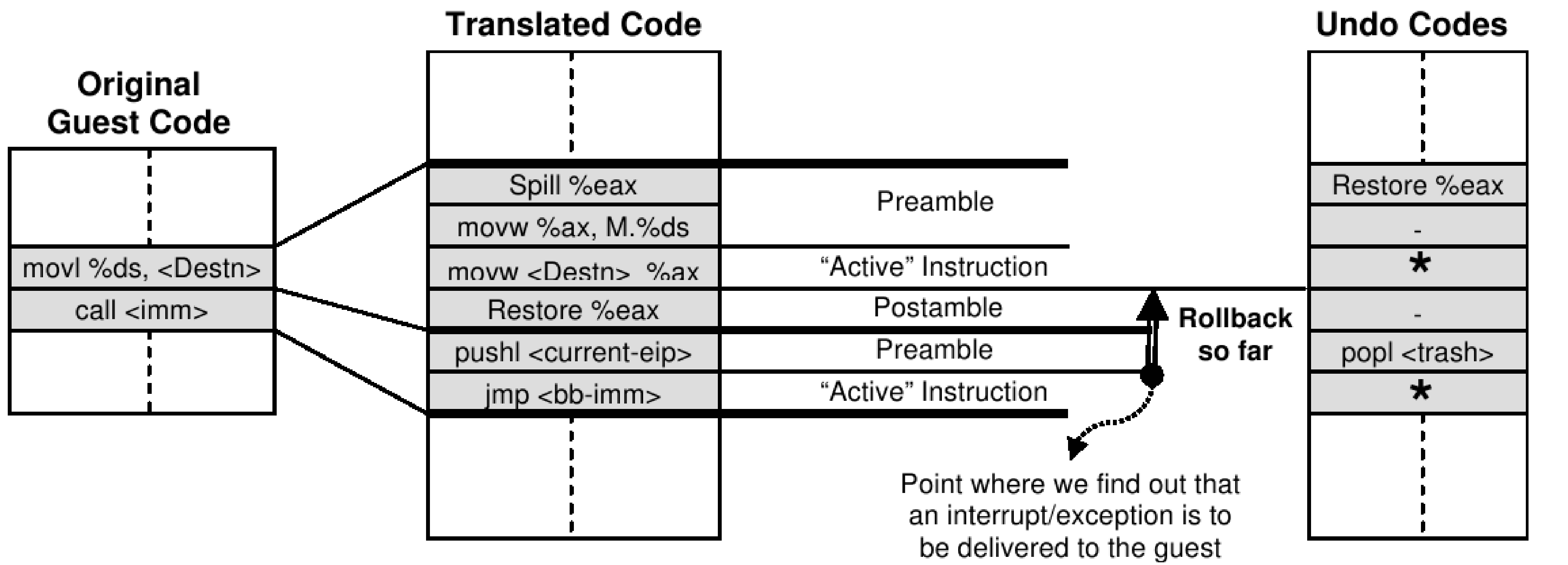


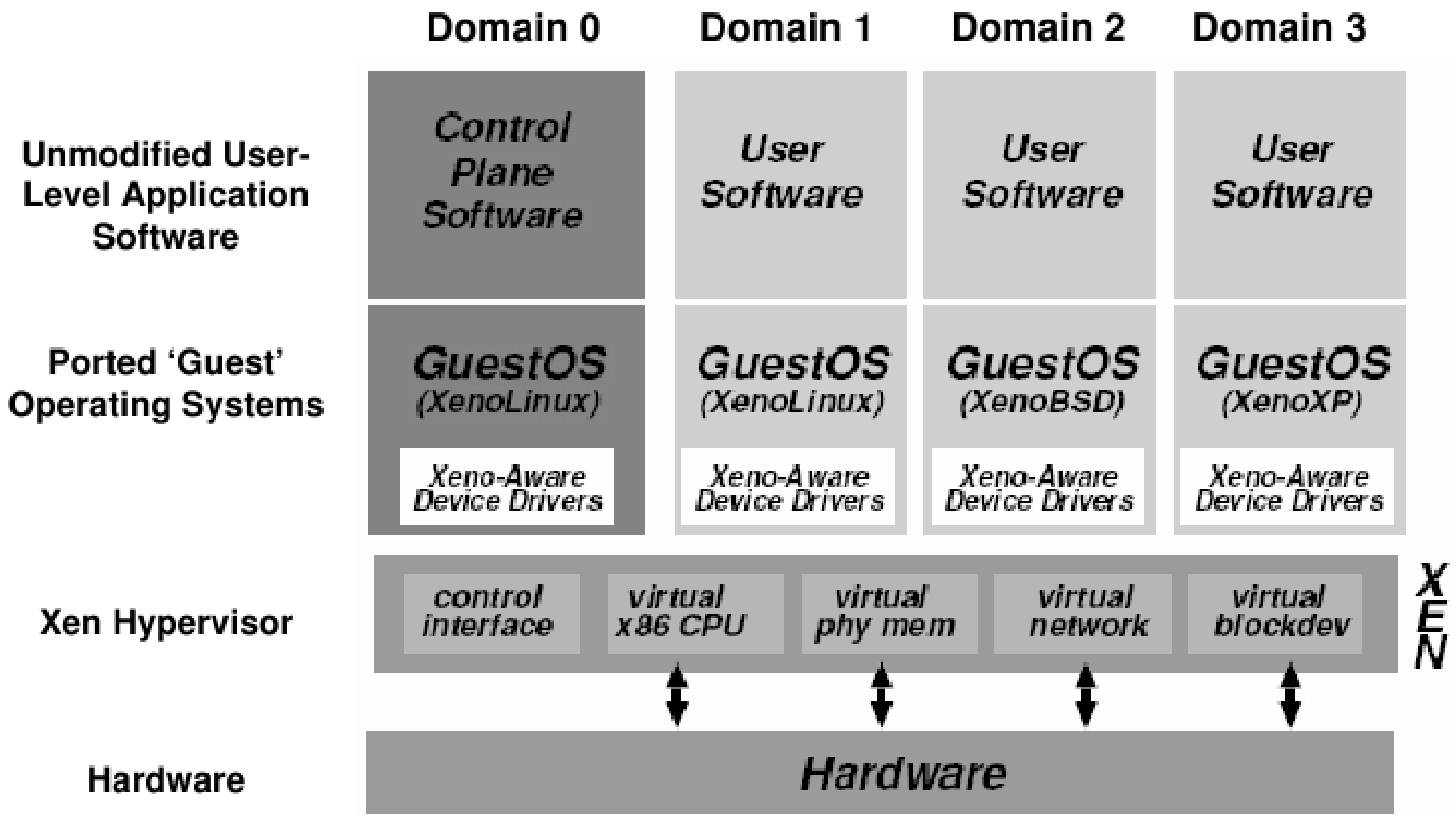
Figure 3: Precise Delivery of Interrupts/Exceptions in VDebug

Paravirtualization

- Trade 100% interface compatibility for performance
  - Fully compliant with ABI (Apps run unmodified)
  - Guest OS-es must be modified to use VMM's interface
- Guest OS-es are Virtualization aware
  - Privileged instruction are replaced by hypervisor calls
- These VMs assume Popek-Goldberg Theorem 1
  - No need for interpretation / translation
- Ex: Xen, UML

Xen and the Art of Virtualization

B. Dragovic, K. Fraser, S. Hand, T. Harris, A. Ho, I. Pratt, A. Warfield, P. Barham, and R. Neugebauer. *Xen and the art of virtualization*. In Proc. of the ACM SOSP Oct. 2003.



More Paravirtualization

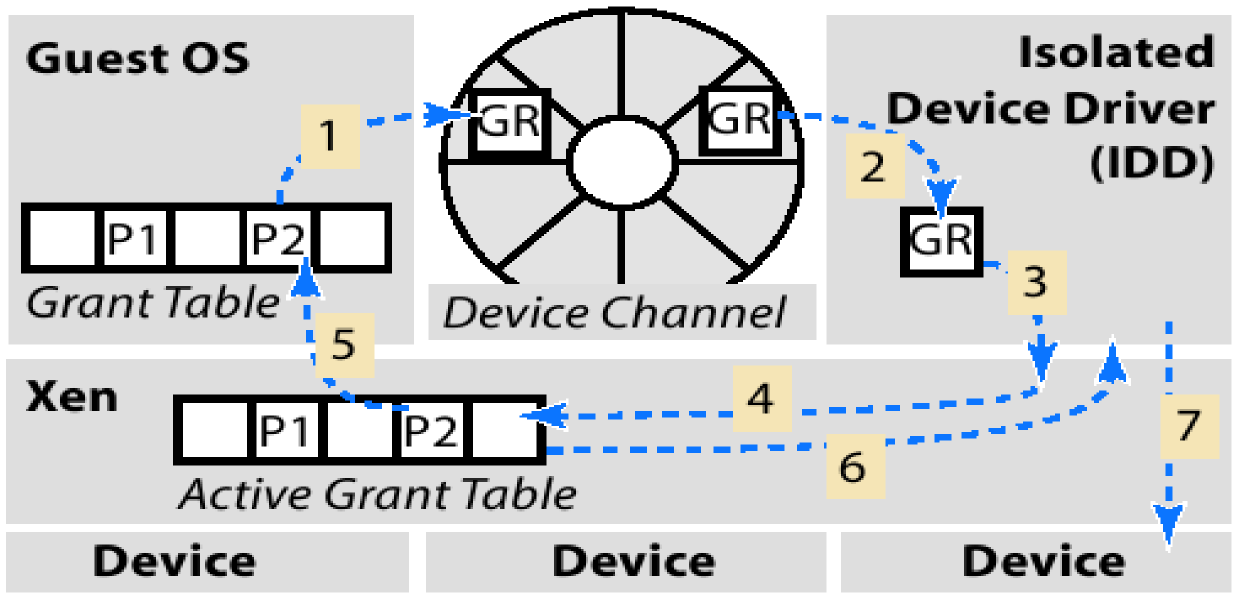
- Virtual time vs Real time
  - Virtualizing time is not always possible, but the Guest-OS can be made aware of this to cope with it
- Expose real resource availability
  - Guest-OS can optimize behavior based on actual information.
- Hypervisor occupies a fixed address
  - Reduces complexity and redundant mappings
- MMU virtualization can be done without shadow page tables

More Paravirtualization

- Guest OS-es can be given protected access to certain HW devices
- The Hypervisor can export a clean set of device interfaces.
- PRE-VIRTUALIZATION
  - Attempt to partially automate the process of modifying the Guest-OS by utilizing the help of the compiler tool chain

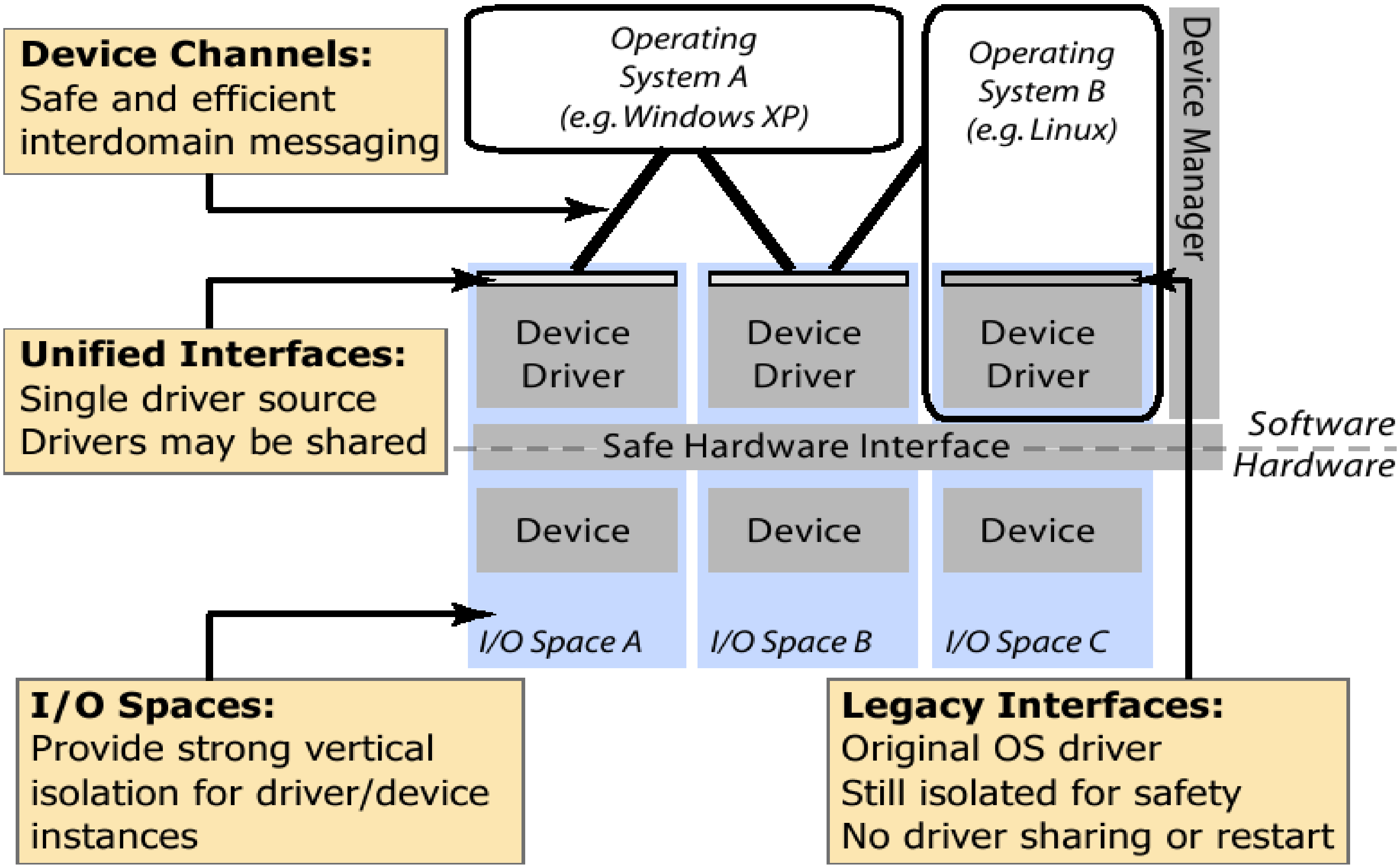
Xen Device Channels

Guest Requests DMA:
1. Grant Reference for Page P2 placed on device channel
2. IDD removes GR
3. Sends pin request to Xen



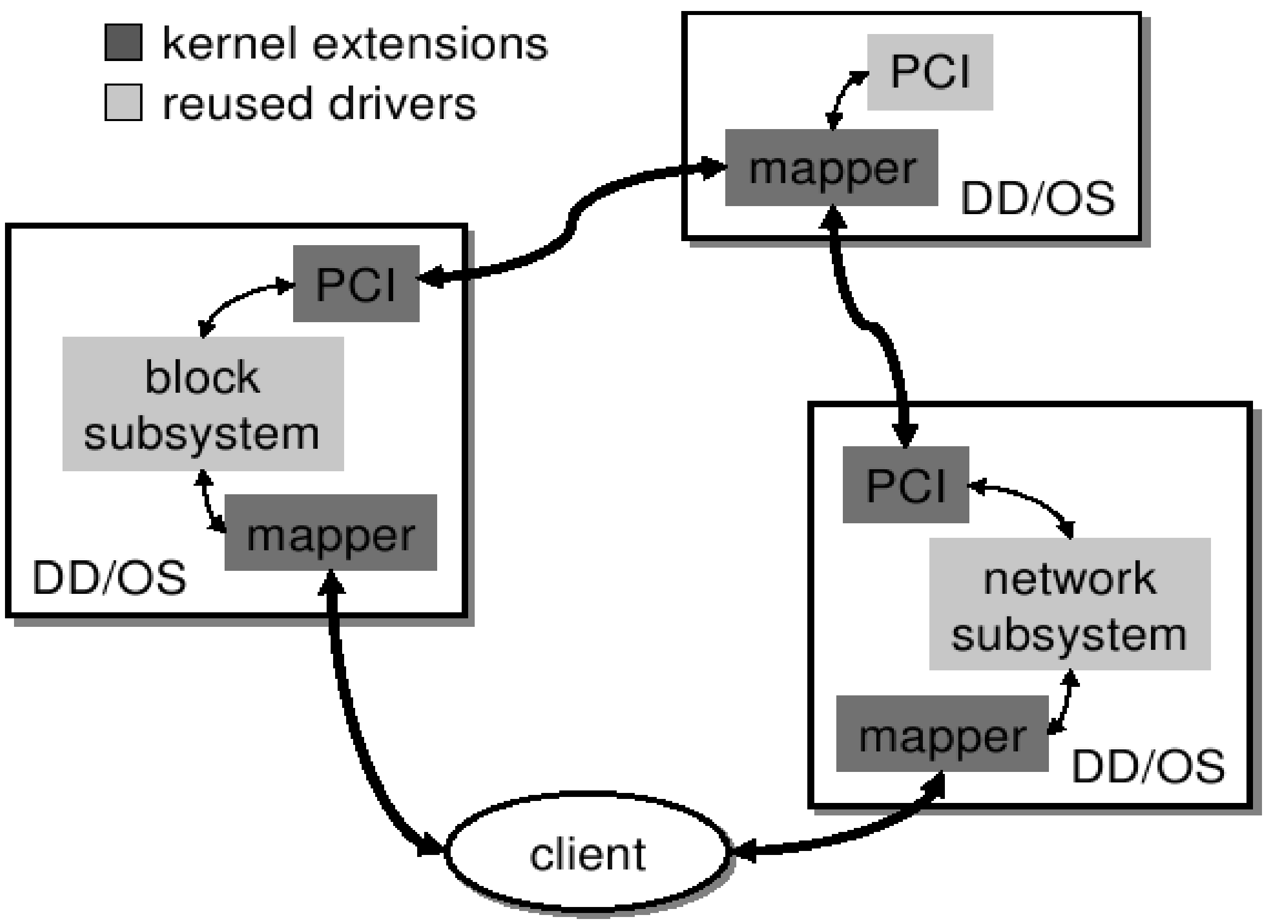
4. Xen looks up GR in active grant table
5. GR validated against Guest (if necessary)
6. Pinning is acknowledged to IDD
7. IDD sends DMA request to device

Sharing Device drivers



Unmodified device-driver reuse

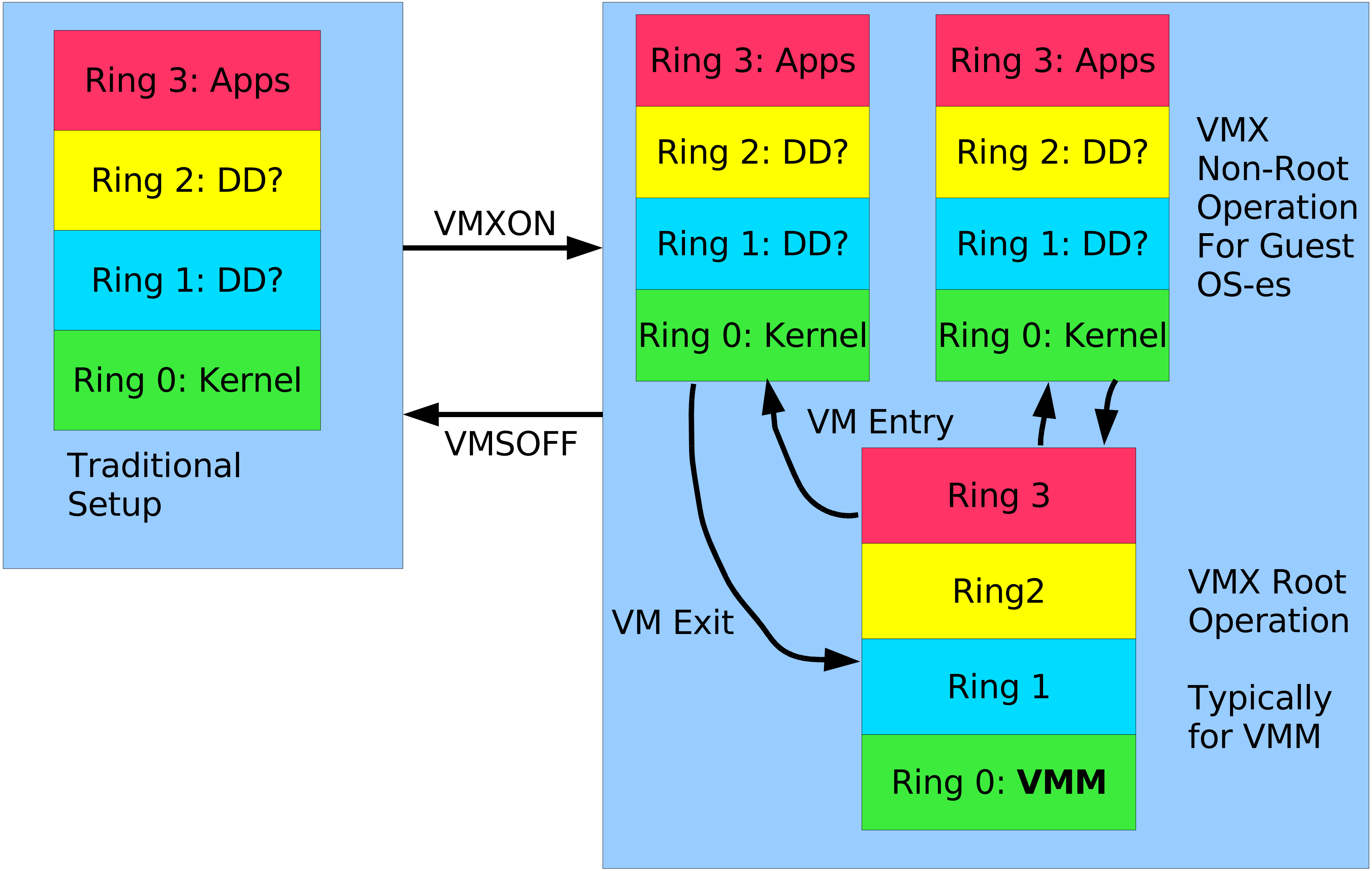
Joshua LeVasseur, Volkmar Uhlig, Jan Stoess, and Stefan Götz, “*Unmodified Device Driver Reuse and Improved System Dependability via Virtual Machines,*” In Proc. of the sixth Symposium on Operating Systems Design and Implementation (OSDI '04), December 6-8, 2004, San Francisco, CA



Hardware Support for Virtualization

- Problems with IA-32 (recap):
  - Non-faulting sensitive instructions
    - Ring levels stored in segment selector
    - System state stored in EFLAGS
  - Segment Descriptor caching
  - TLB flushes due to Guest/VMM transitions
- Proposed solutions
  - Intel VT
  - AMD Pacifica

Intel Virtualization Technology(VT)



What is added?

- VMX root operation mode, or “Ring -1”.
- VMCS – the VM control structure.
- 10 Instructions.
- Changes to the “normal” (VMX non-root) mode operation for some instructions.
- VMM can specify what interrupts / exceptions it wants notification.
- Shadows for control register reads.
- I/O virtualization support.

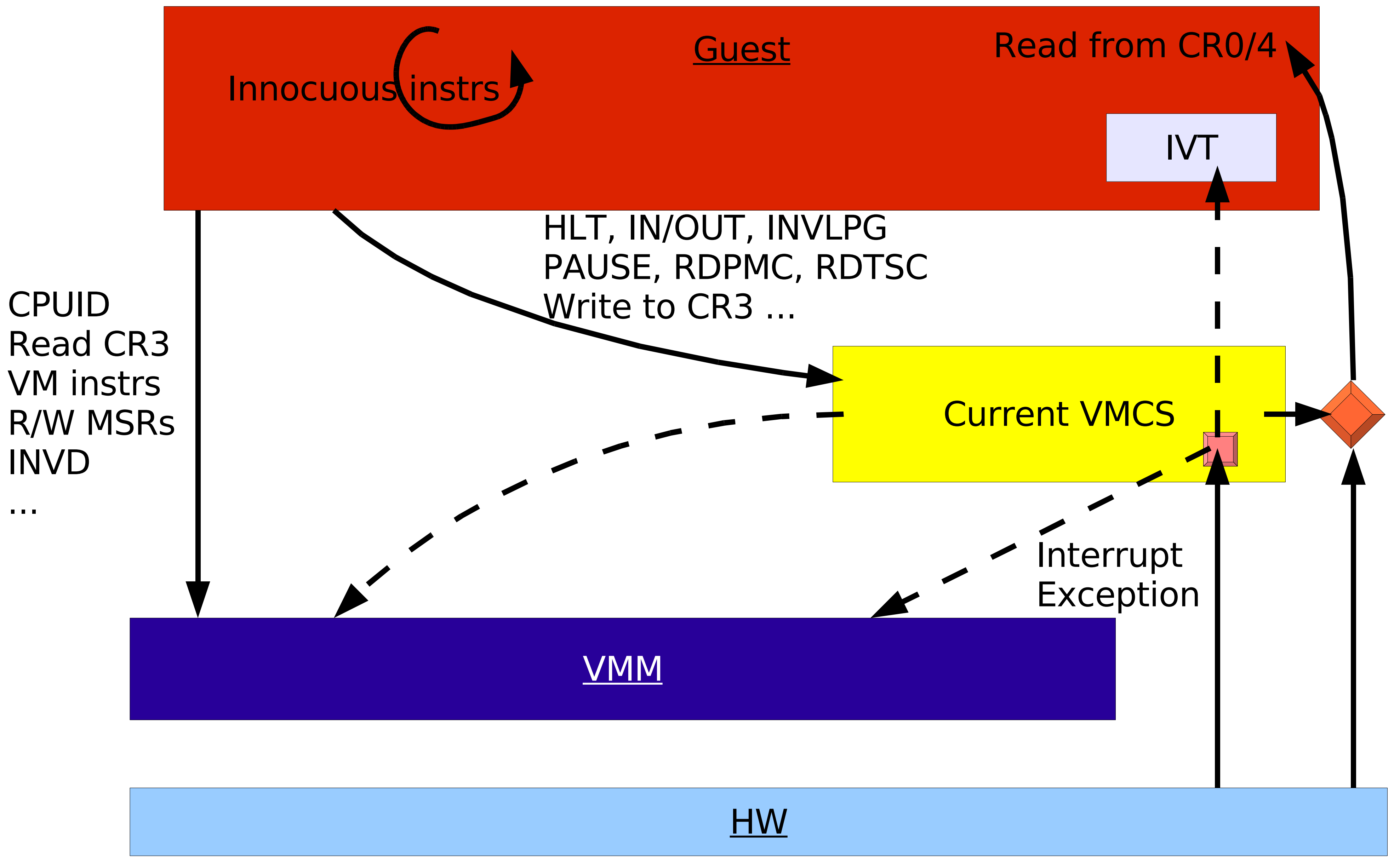
VMCS structure

- Guest-state area
  - Guest register state, Activity / Interruptibility state
- Host-state area
  - Host register state
- VM execution control fields
  - Determine of there must be a VM-exit for:
    - Pin based Interrupts / NMIs
    - Some instructions like HLT, INVLPG, RDPMC, read/write Control regs, etc
  - Exception bitmap
  - I/O bitmap

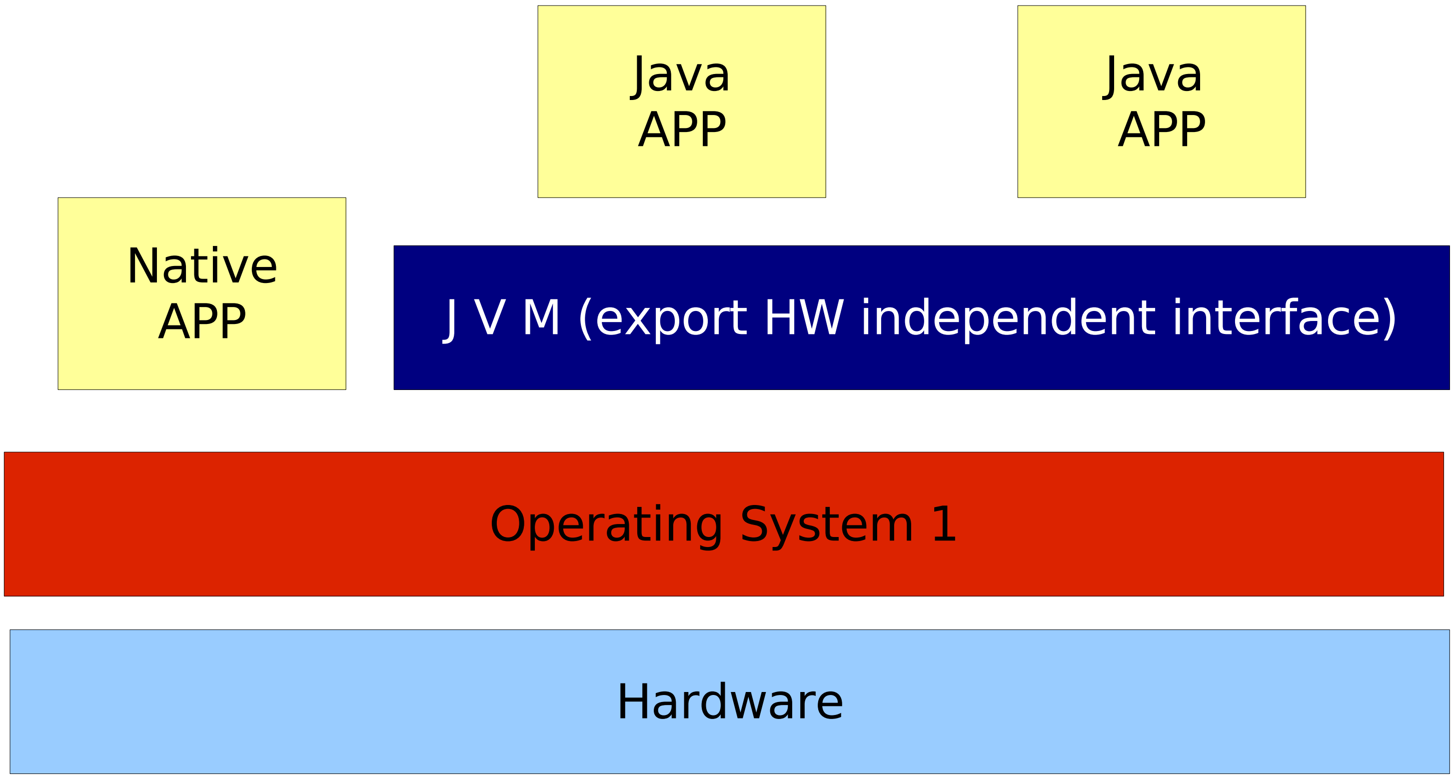
VMCS structure (cont)

- VM execution control fields (cont)
  - Time-stamp counter offsets
  - Guest/Host Masks and Read Shadows for CR0 / CR4
- VM-entry / VM-exit control fields
  - MSR load options
  - Event injection
- VM-exit information fields.

The Virtualization



Language Run-times



IO Virtualization Support

- Desirable:
  - Device emulation: Legacy / new interface
  - Device assignment to VMs
  - Device assisted sharing
- DMA remapping using IO page tables
  - IO-TLB to speed up translation
  - DMA isolation and VM protection
  - Facilitates device assignment and VM relocation

AMD Pacifica

- No extra rings
- VMM and guest run in different address spaces (worlds)
- Support for fast world-switches
  - Support for tagged TLBs
- Virtual Machines controlled through VMCBs
- Interrupt virtualization and Virtual interrupts
- Intercepts
  - Instruction, Interrupt, exception, I/O
- IOMMU / GART + DEV checking

Security considerations

Intel LaGrande(*) and AMD64(#) architectures

- Secure startup(*#)
  - Trusted Platform Module (TPM)
- Protected Input / Output(*)
  - Encrypted Keyboard / mouse / USB input
  - Protected pathway to frame-buffer
- Attestation(*)
- Secure storage of Keys(*)
- Security Exception(#)
  - Redirect INITS to scrub sensitive information