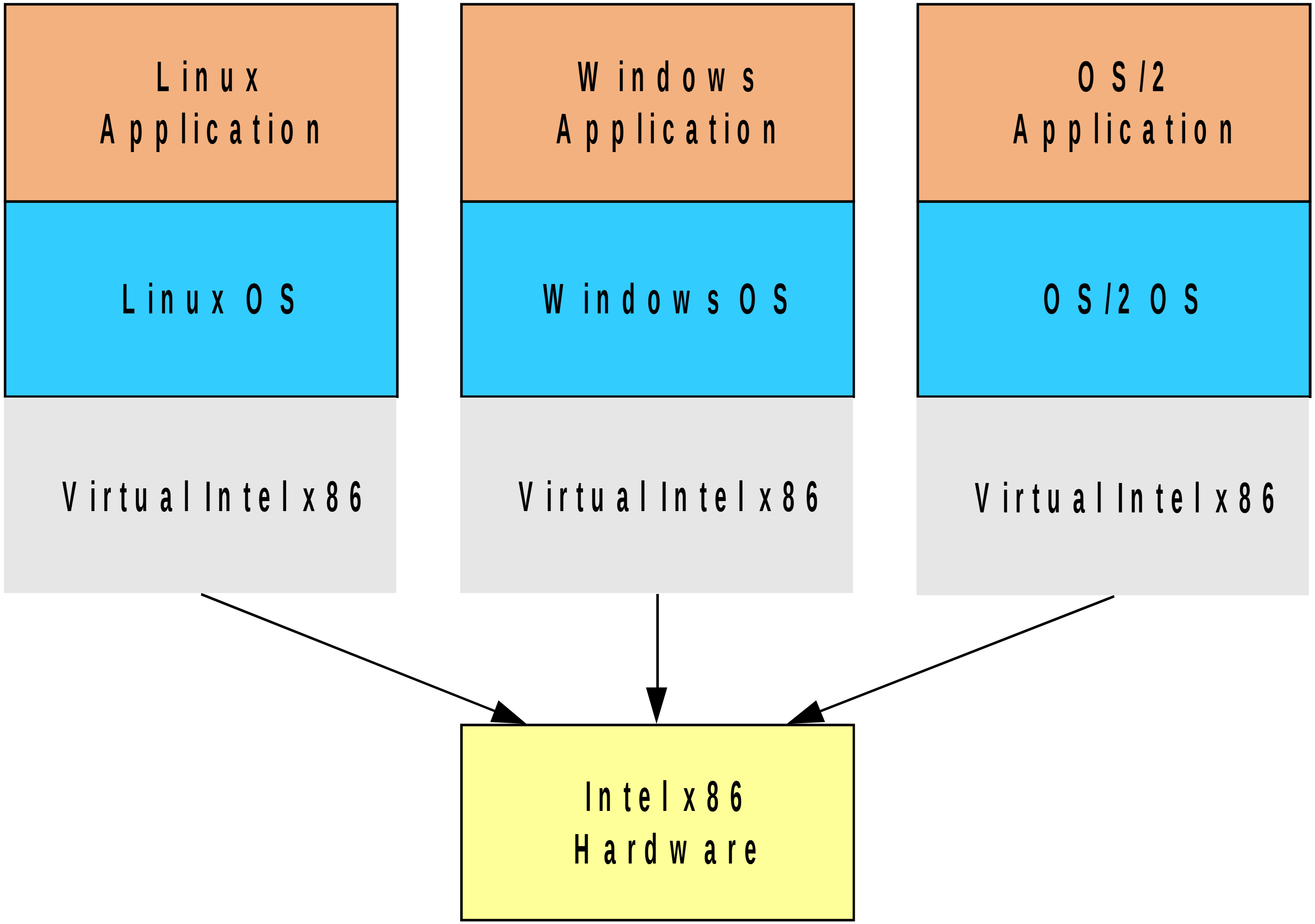
System Virtual Machines

- Introduction
- Key concepts
- Resource virtualization
  - processors
  - memory
  - I/O devices
- Performance issues
- Applications

Introduction

- System virtual machine
  - capable of supporting multiple system images
  - each *guest* OS manages a set of virtualized hardware resources
  - VMM owns the real system resources
  - VMM allocates resources to guest OS by partitioning or time-sharing
  - guest OS allocates resources to its user programs
  - each virtual resource may not have physical resource
  - see Figure 8.1

Introduction (2)



Key Concepts

- Outward appearance
- State management
- Resource control
- Native and hosted virtual machines

- Several concepts are simplified
  - same guest and host ISA
  - uniprocessor systems

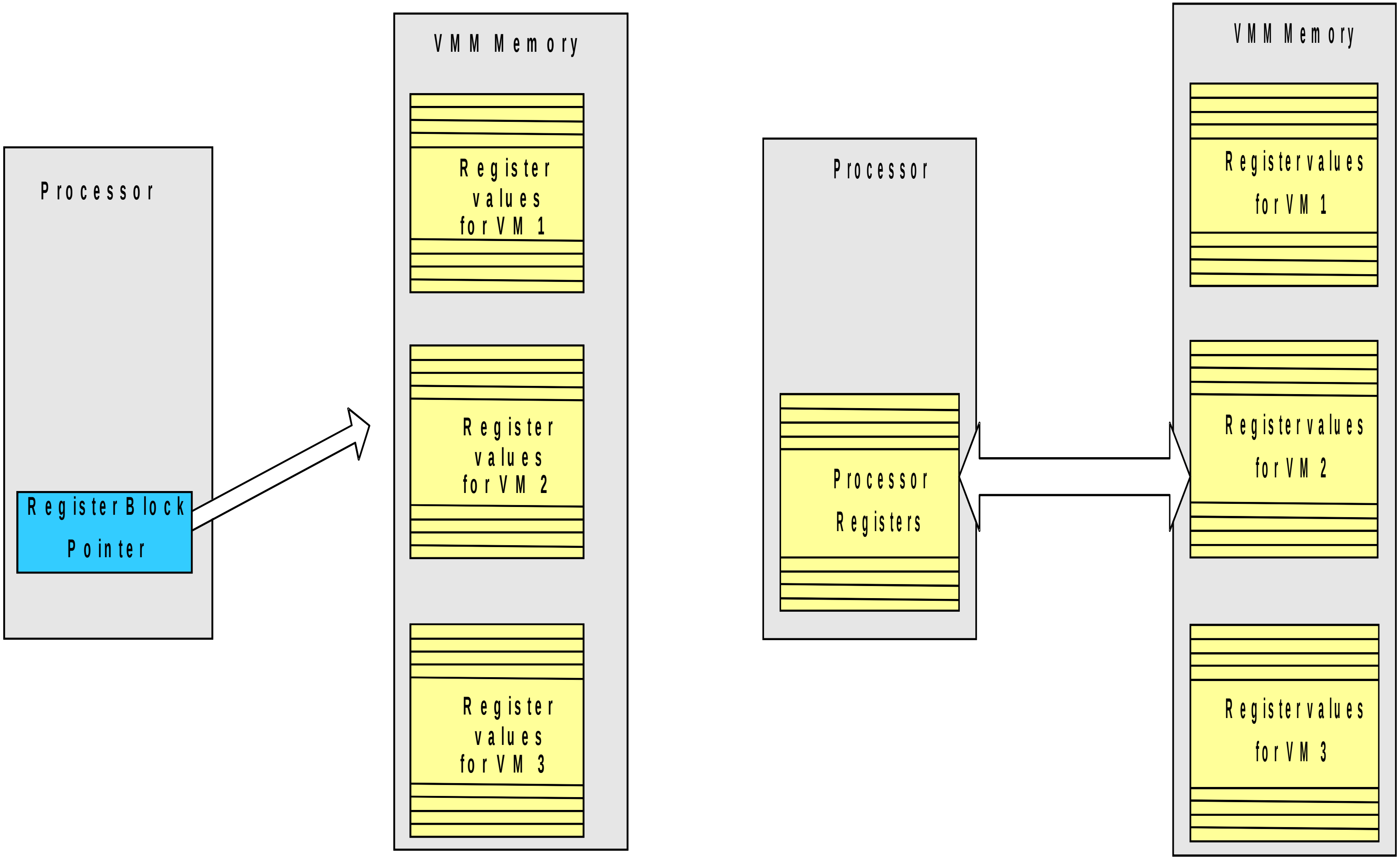
Outward Appearance

- Create an illusion of multiple machines.
- Illusion in software
  - no replication of hardware resources
  - switch to move devices from one VM to the other
- Replication of hardware resources
  - devices used directly by each user are replicated
  - rest of the hardware is shared
- Hosted VM
  - one OS more important than the other
  - UI of host OS provides way to display UI of the second

State Management

- Refers to how each individual guest state is managed by the SVM
  - each guest OS has an architected state
  - host resources may not be adequate
- Fixed location for all guest state in host
  - VMM manages pointer and switching
  - indirection can be very inefficient (Figure 8.3a)
- Copy approach
  - more efficient (Figure 8.3b)
  - essential to allow direct execution of native code

State Management (2)

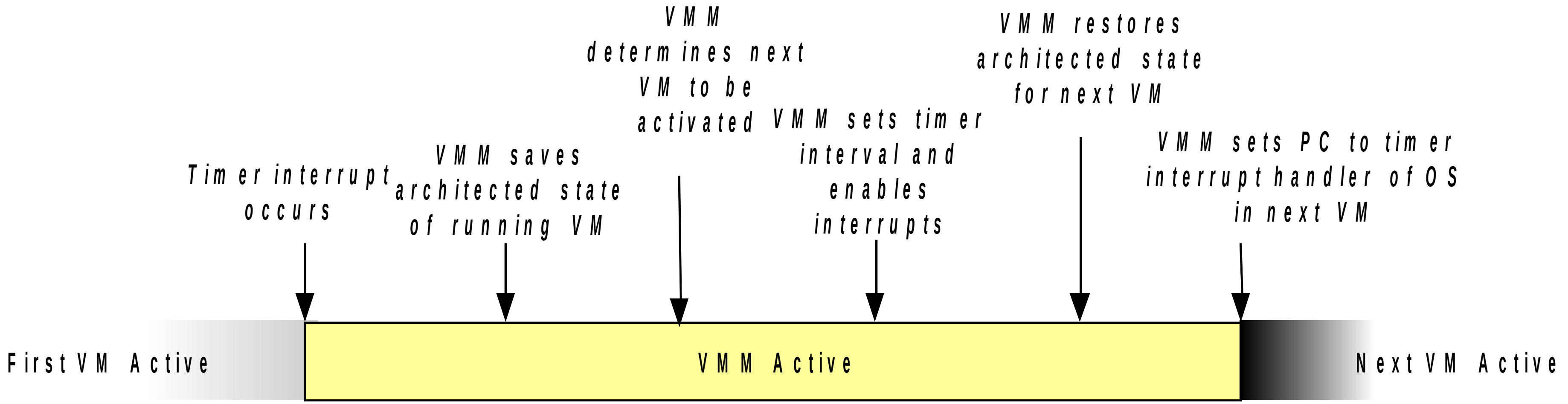


Resource Control

- Refers to how the VMM maintains overall control of all hardware resources.
- Scheme similar to time-sharing OS
  - VMM intercept accesses to privileged resources
  - get control on all privileged instructions
  - VMM handles the timer interrupt (Figure 8.4)
  - similar tradeoffs between fair scheduling and large switching overhead

VMM Timesharing

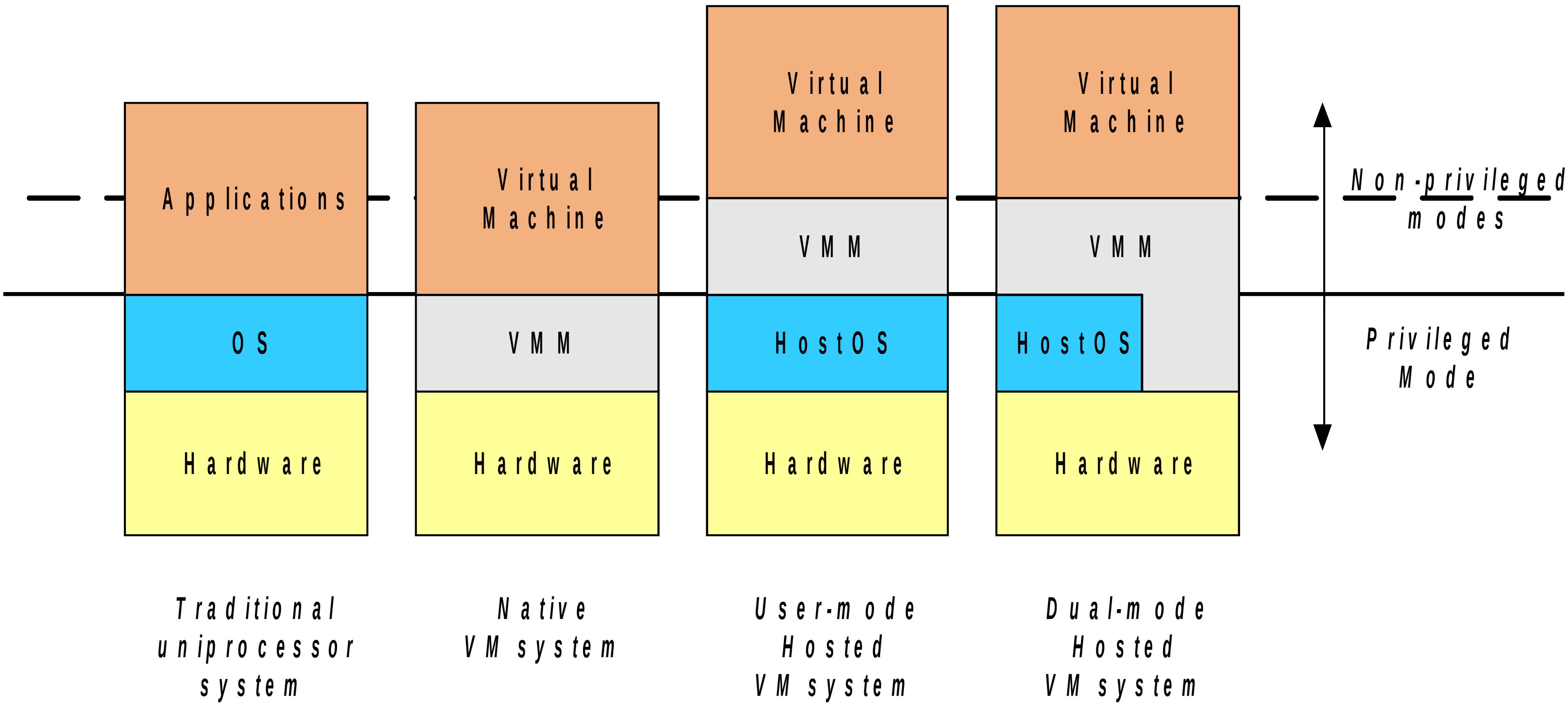
- VMM timeshares resources among guests
  - similar to OS timesharing



Native and Hosted VM

- Refers to the runtime privilege level of the VMM (and OS).
  - for efficiency, some part of VMM should have higher privileges
- Figure 8.5
  - analogous relationship to OS and user programs
  - *native VM system:* only the VMM operates in privilege mode
  - *hosted VM:* VMM installed on top of existing OS
    - some or no part of VMM in privilege mode

Native and Hosted VM (2)



Resource Virtualization – Processors

- Techniques to execute guest instructions
  - emulation
  - direct native execution
- Emulation
  - interpretation or binary translation
  - necessary if different host and guest ISAs
- Direct native execution
  - same host and guest ISAs required
  - may still require emulation of some instructions

Conditions for ISA Virtualizability

- Conditions laid out by Popek and Goldberg.
- Assume native system VMs
  - VMM runs in system mode
  - all other software runs in user mode
- Other assumptions
  - hardware consists of processor and uniformly addressable memory
  - processor can operate in two modes, user and system
  - some subset of instructions only available in system mode
  - relocation register available for memory addressing

Privileged Instructions

- Instructions that trap if the machine is in *user* mode, and does not trap if the machine is in *system* mode.
- LPSW (Load Processor Status Word)
  – PSW can change the state of the CPU
  – can also change the instruction address (PC)
- SPT (Set CPU Timer)
  – can change the CPU interval timer

Privileged Instructions (cont...)

- LRW (Load Real Address)
  - translate a virtual address, save corresponding real address in a specified GPR
- POPF (Pop Stack into Flags Register)
  - replace flag register with top of memory stack
  - *interrupt-enable* flag can only be modified in system mode
  - no *trap* in user mode

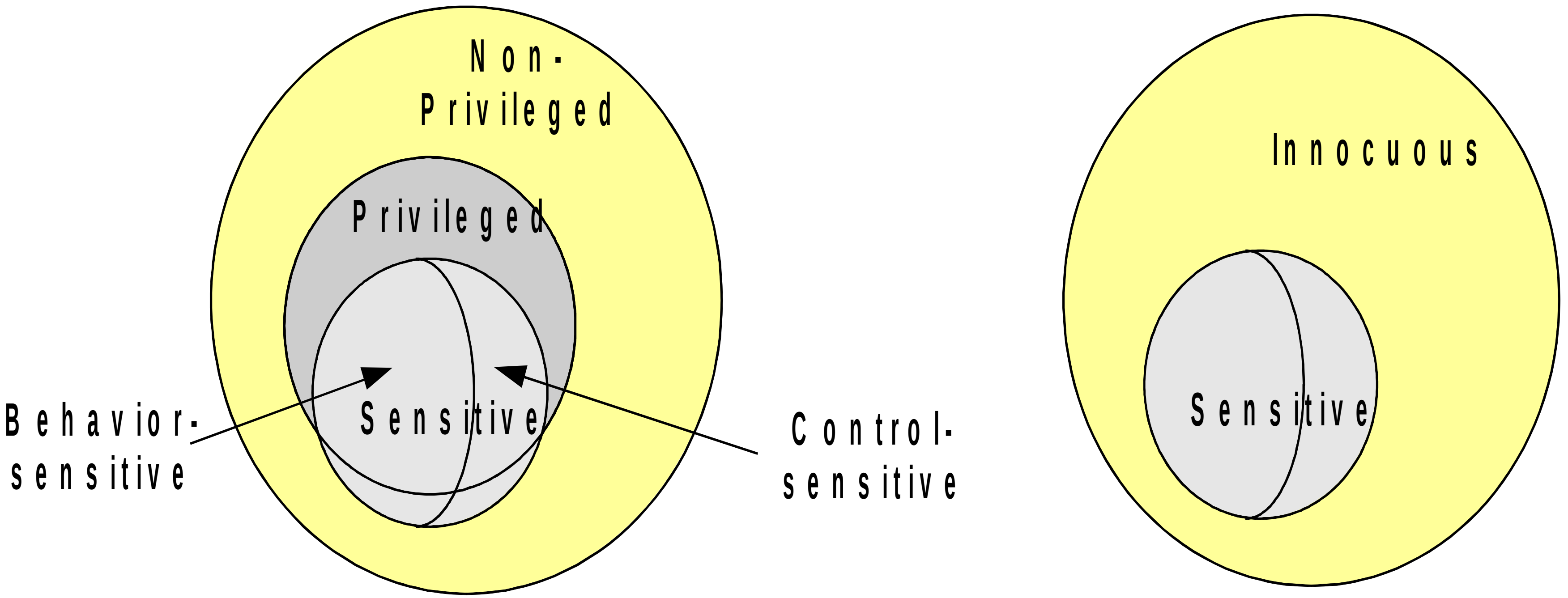
Sensitive Instructions

- These specify instructions that interact with hardware.
- Control-sensitive instructions
  – can change the configuration of system resources
  – e.g., physical memory assigned to a program
  – e.g., LPSW – change mode of operation
  – e.g., SPT – change CPU timer value

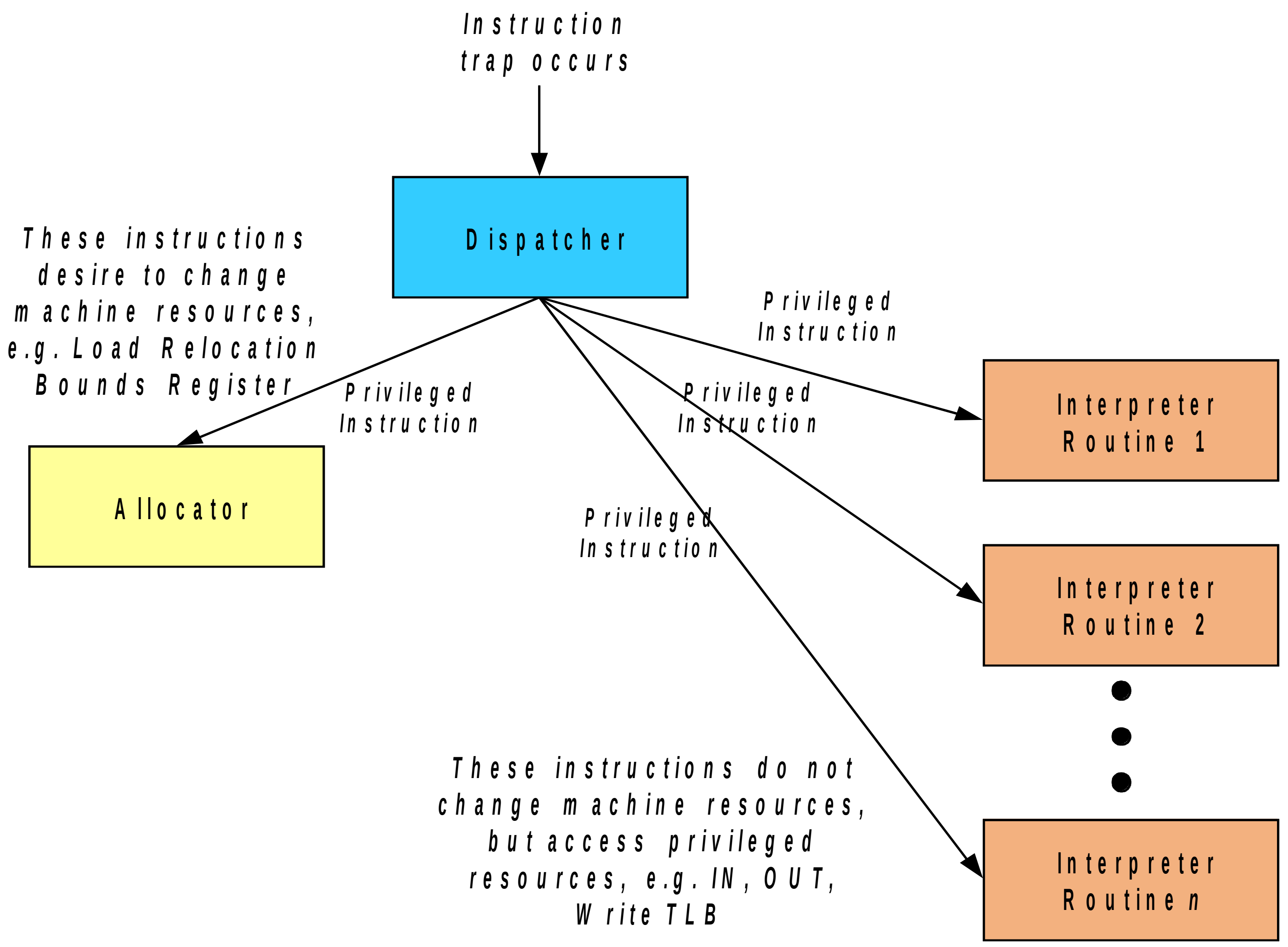
Sensitive Instructions (cont…)

- Behavior-sensitive instructions
  - behavior or results depend on configuration of resources
  - e.g., LRA – depends on mapping (state) of real memory resource
  - e.g., POPF – depends on mode of operation
- Innocuous instructions
  - neither context-sensitive nor behavior-sensitive
- see Figure 8.6

Instruction Types – Summary



Components of a VMM



Components of a VMM (2)

- Dispatcher
  - control module, called on hardware traps
  - decides the next module to be invoked
- Allocator
  - decides allocation of system resources
  - invoked by dispatcher to change machine resource allocation for VMs
- Interpreter routines
  - emulates trap functionality for each user VM
  - all traps except resource re-assignment traps

Properties for a True VMM

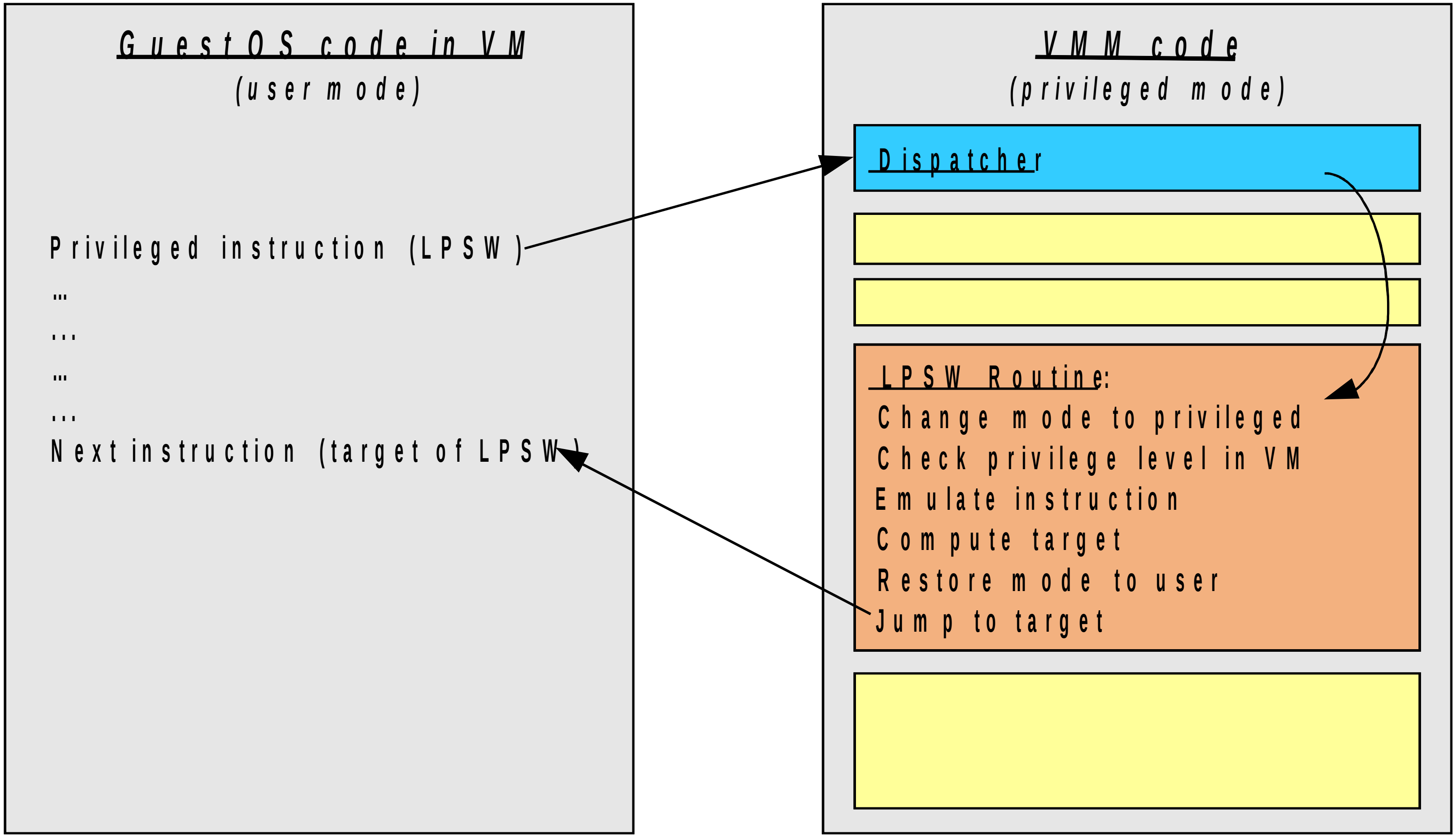
- Efficiency
  - All *innocuous* instructions *must* be natively executed
- Resource control
  - impossible for guest s/w to *directly* change system resource configurations
- Equivalence
  - guaranty of identical behavior
  - allowed exceptions
    - performance can be slower
    - available resources can be limited
    - differences in performance due to changed timings

Requirement for True VMM

- For any third-generation computer, a VMM may be constructed if the set of sensitive instructions for a computer is a subset of the set of privileged instructions
  - sensitive instructions always trap in user mode
  - non-privileged instructions execute natively

Handling Privileged Instruction

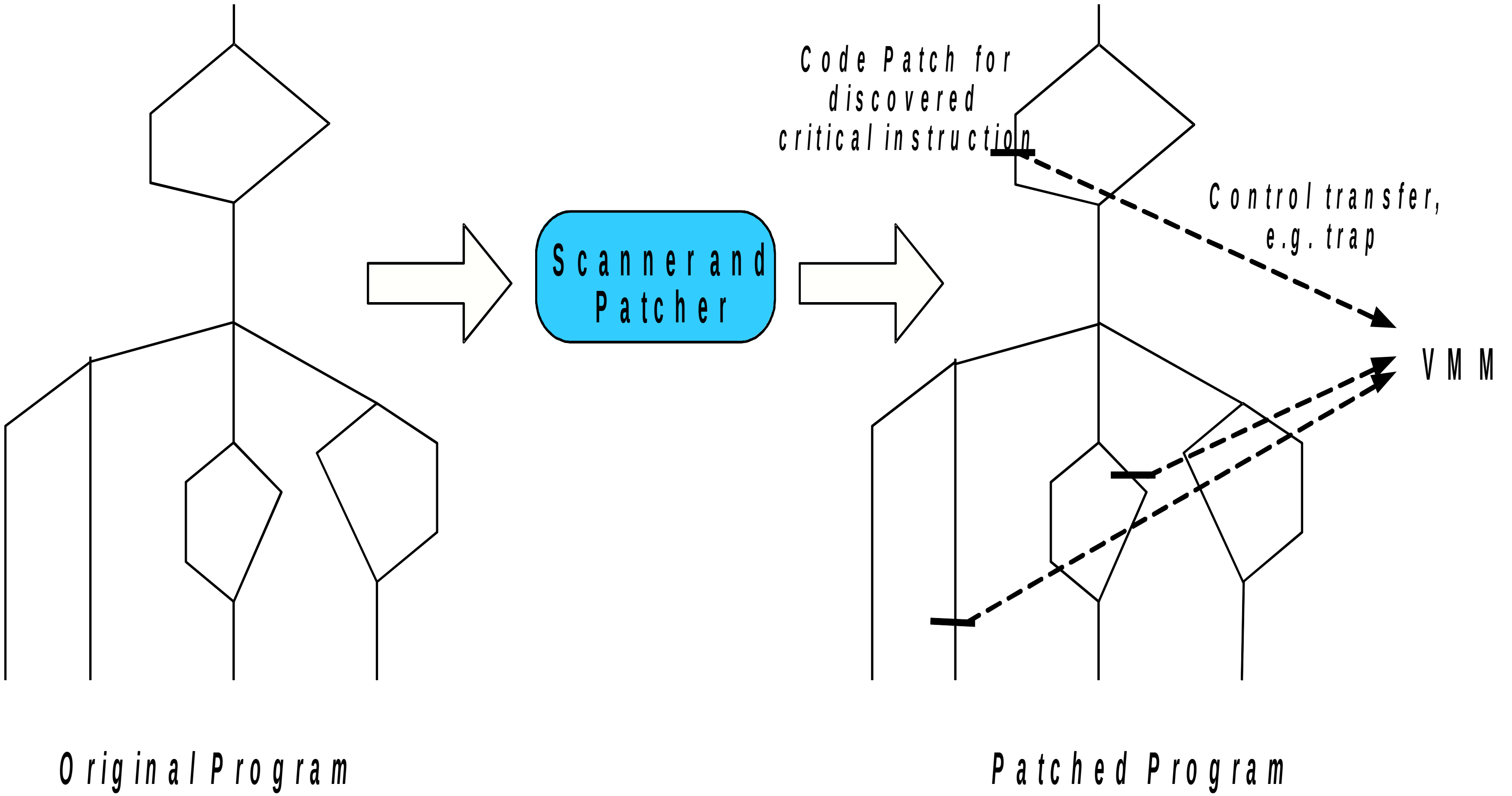
- Privileged instruction traps in the guest OS



Problem Instructions

- Sensitive instructions that are not privileged
  - POPF instruction in the Intel IA-32
  - IA-32 not virtualizable by Popek-Goldberg rules
- Handling problem instructions
  - interpret all guest software
  - scan and patch problem instructions before execution
  - see Figure 8.11

Patching Problem Instructions



Patching Problem Instructions (2)

- VMM takes control at the head of each basic block.
- Scan to find problem instructions.
- Replace with trap to VMM.
- Place another trap at end of basic block.
- Patched basic blocks can be *chained.*
- Mostly similar to binary translation.

Caching Emulation Code

- High frequency of sensitive instructions requiring interpretation increases VMM overhead
  – cache interpreter actions in code cache
  – cache block containing the problem instruction
- Each instance of the problem instruction in the code associated with a distinct piece of cache code
  – make code instance-specific and optimize
- Simpler management of cached code
  – cached code executed in system mode

Resource Virtualization – Memory

- Generalizes the concept of virtual memory
- Virtual memory basics
  - application provided a *logical* view of memory
  - OS manages actual *real* memory
  - page tables provide logical-physical mapping
  - TLBs cache most common mappings
- VMM distinguishes between *real* memory and *physical* memory
  - VMM does real-physical memory mapping

VMM Memory Support

- VMM mechanism to virtualize memory
  – maintain a per-VM *real-map table*
  – maps real pages to physical pages
  – VMM maintains a distinct swap space
- Additional indirection layer may be inefficient
  – virtualize architected page tables
  – virtualize architected TLB

Resource Virtualization – I/O

- Virtualization of I/O is difficult
  - large number of I/O devices
  - each I/O device controlled in specific manner
  - OS have to deal with similar issues
- Virtualization Scheme
  - provide VMs with virtual version of a device
  - intercept VM requests made to virtual device
  - convert request, perform equivalent action

Virtualizing Devices

- Dedicated devices
  - display, keyboard, mouse etc., for each user
  - no device virtualization necessary
  - device requests could bypass the VM
- Partitioned devices
  - smaller *virtual* disks for each user
  - VMM use map to translate parameters
  - status information from the device also needs translation and reflection in the map

Virtualizing Devices (cont...)

- Shared devices
  - network adapter, virtual network address for a VM
  - maintain state information for each guest VM
  - translate device outgoing/incoming requests
- Spooled devices
  - shared at higher granularity, e.g., printer
  - two-level spool tables in OS and VMM
  - VMM schedules requests from multiple guest VMs

Performance Degradation

- Setup
  - initialize the state of the machine
- Emulation
  - sensitive instructions, maybe others
- Interrupt handling
  - handling interrupts generated by the guest programs
- State saving
  - save/restore state of VM during switch to VMM
- Book-keeping
  - special operations to maintain equivalent behavior
- Time elongation
  - some instructions may require more processing time

VM Assists

- Piece of hardware that improves performance of an application when running on a VM.
- May not always improve performance
  - improve user program-VMM system-mode switches
  - improve address translation performance
- VM assists can help improve performance of
  - instruction emulation
  - other aspects of VMM
  - the user-mode system running as the guest
  - specific types of guest systems

Instruction Emulation Assists

- Emulation of privileged instructions in the guest VM is a cause of fundamental overhead
  - causes interrupt that is handled by the VMM
  - VMM emulation depends on whether guest VM in user or system mode when instruction called
- Assist for LPSW on system/370
  - check state of guest VM
  - provides hardware-assisted instructions to modify physical resources
- Depends on VM system implementation
- The overhead of the *trap* still remains
  - eliminates overhead of emulation and mode switching

VMM Assists

- Context switch
  - hardware to save/restore registers, machine state
- Decoding of privileged instructions
  - helps certain critical parts of the emulation
- Virtual interval timer
  - precise timer for all guest VMs to schedule jobs
- Adding to the instruction set
  - to help commonly executed VMM parts

Improve Guest VM Performance

- Requires guest system to be VMM aware
  - avoid duplication of functionality
  - provide VMM with additional information (handshaking), e.g., DIAGNOSE instruction
- Example; non-paged mode
  - disable dynamic address translation in guest VM
  - no translation from virtual to real address
  - translation from real to physical done by VMM
- Paravirtualization
  - modify guest OS to work around difficult to virtualize ISA features
  - Xen for the IA-32, eliminates code detection, patching, shadow page tables

Applications

- Implementing multiprogramming
- Multiple single-application virtual machines
- Multiple secure environments
- Mixed-OS environments
- Legacy applications
- Multiplatform application development
- Gradual migration to new system
- New system software development
- Operating system training
- Help desk support
- Operating system instrumentation
- Event monitoring
- System encapsulation and checkpointing