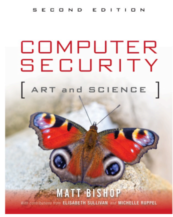


Virtual Machines

Appendix D

Outline

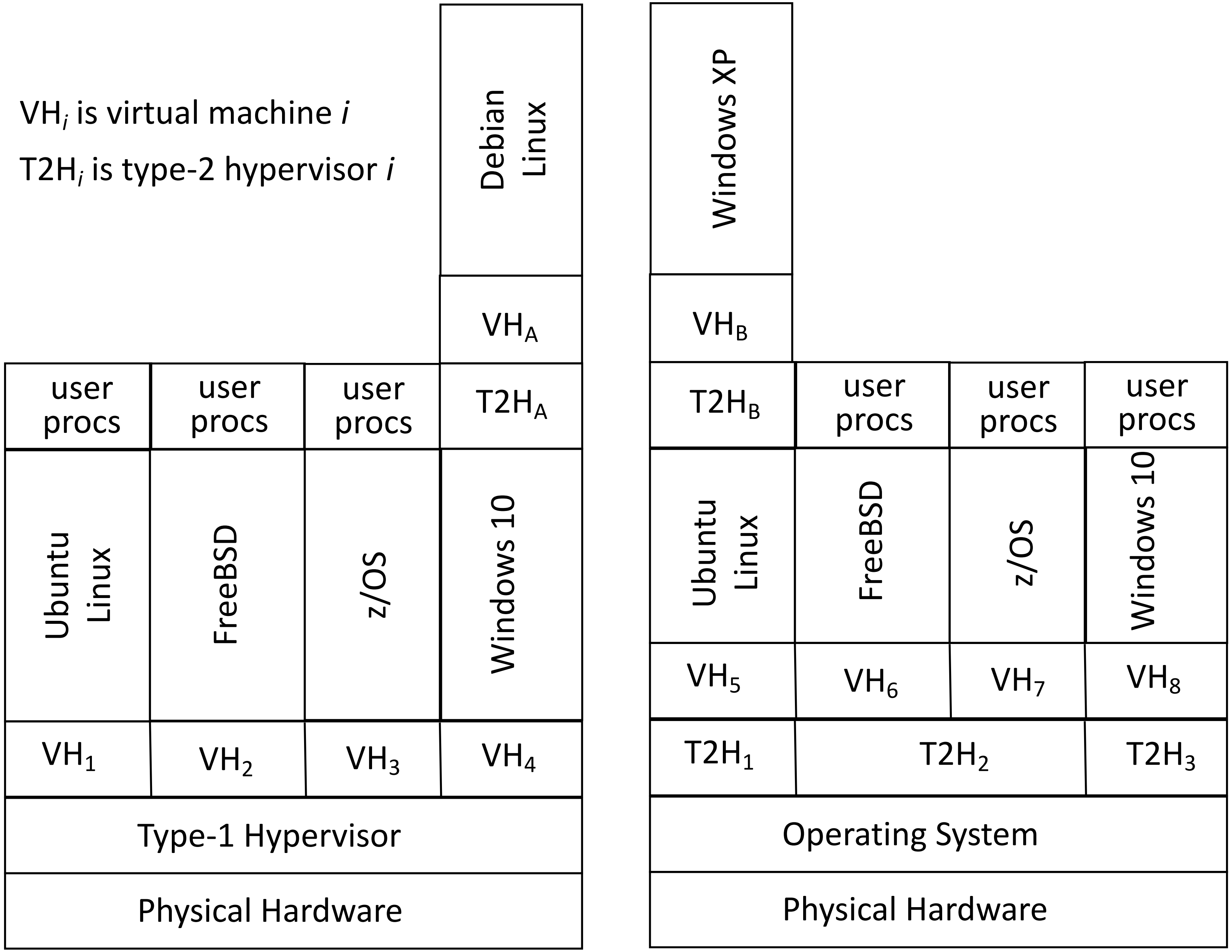
- Virtual Machine Structure
- Virtual Machine Monitor
  - Privilege
  - Physical Resources
  - Paging

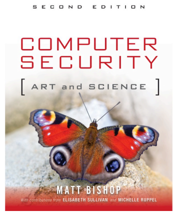
What Is It?

- *Virtual machine monitor* (VMM) or *hypervisor* virtualizes system resources
  - Provides interface to give each program running on it the illusion that it is the only process on the system and is running directly on hardware
  - Provides illusion of contiguous memory beginning at address 0, a CPU, and secondary storage to *each* program
- *Type-1 hypervisor* runs directly on the hardware
- *Type-2 hypervisor* runs as a process on a regular operating system

VH$_i$ is virtual machine *i*

T2H$_i$ is type-2 hypervisor *i*





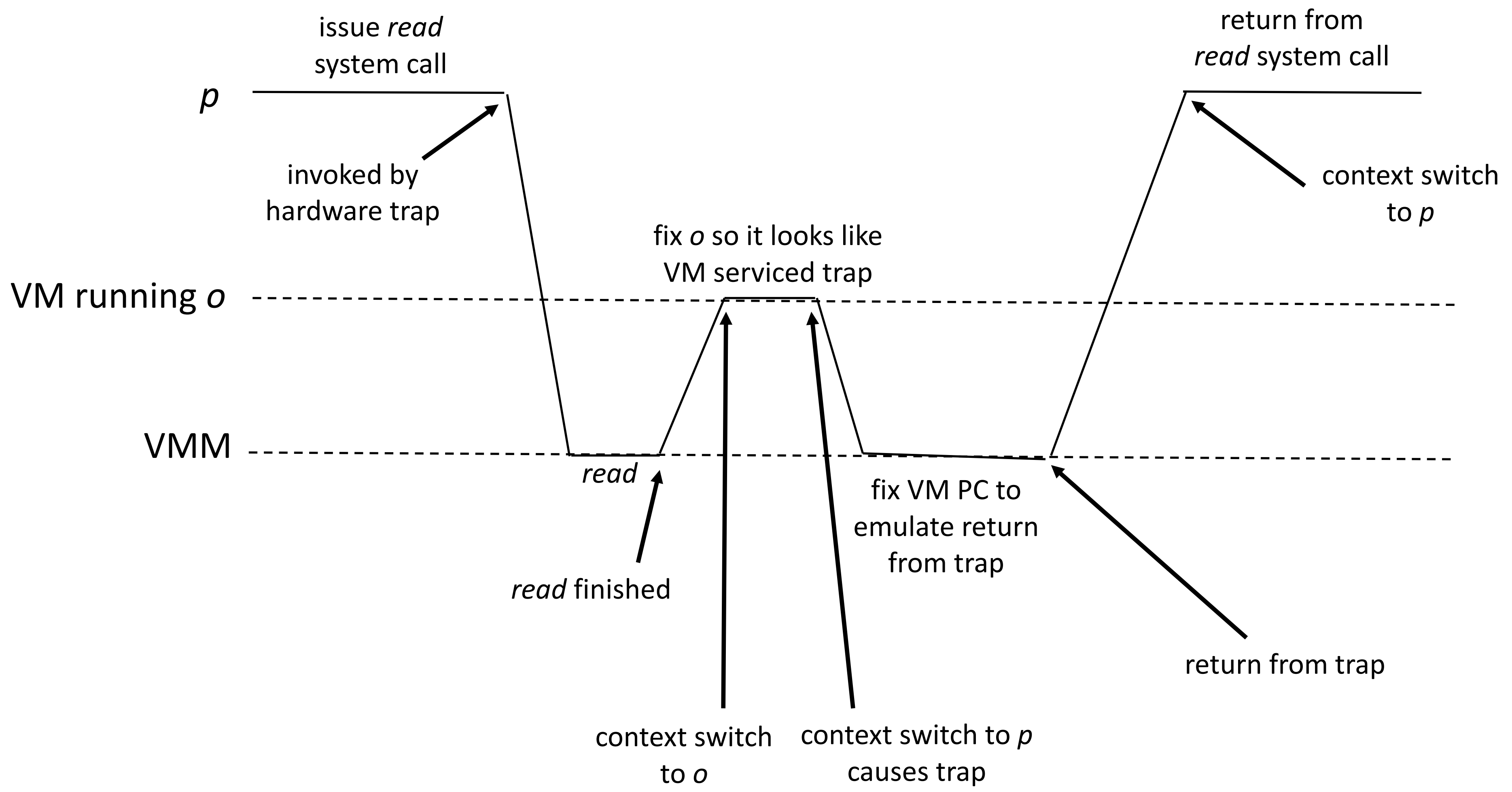
Privileged Instructions

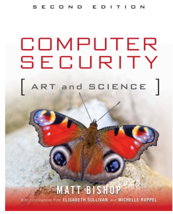
1. VMM runs VM with operating system *o*, which is running process *p*
   - *p* tries to read, so privileged operation traps to hardware
2. VMM invoked, determines trap occurred in VM
   - VMM updates state of VM to make it look like hardware invoked *o* directly, so *o* tries to read, causing trap
3. VMM does read
   - Updates VM to make it seem like *o* did read
   - Transfers control to *o*

Privileged Instructions

4. *o* tries to switch context to *p*, causing another trap
5. VMM updates VM running *o* to make it appear *o* did context switch successfully
    - Transfers control to *o*, which (as *o* apparently did a context switch to *p*) returns control to *p*

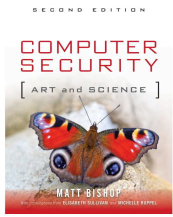
Privileged Instructions





Privilege and VMs

- *Sensitive instruction* discloses or alters state of processor privilege
- *Sensitive data structure* contains information about state of processor privilege

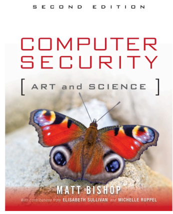


When Can VM Be Run?

- Can virtualize an architecture when:
  1. All sensitive instructions cause traps when executed by processes at lower levels of privilege
  2. All references to sensitive data structures cause traps when executed by processes at lower levels of privilege

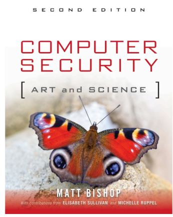
Example: VAX System

- 4 levels of privilege (user, supervisor, executive, kernel)
  - CHMK changes privilege to kernel level
    - Sensitive instruction
    - Causes trap *except* when executed in kernel mode; meets rule 1
  - Page tables have copy of PSL, containing privilege level
    - Sensitive data structure
    - If user level processes prevented from altering page tables, trying to do so will cause a trap; meets rule 2



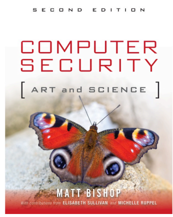
Multiple Levels of Privilege

- Hardware supports *n* levels of privilege
  - So each VM must appear to do this also
- But only VMM can run at highest level
  - So *n* – 1 levels available to each VM
- VMs must virtualize levels of privilege
  - Technique called *ring compression*



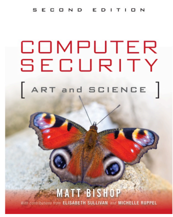
Virtualize Privilege Levels

- VAX/VMM must emulate 4 levels of privilege
  - Cannot allow any VM to enter kernel mode, and thereby bypass VMM
  - But VAX/VMS requires all four levels!
- Virtualize executive, kernel privilege levels
  - Conceptually, map both to physical executive level
  - Add VM bit to PSL; if set, current process is on VM
  - VMPSL register records PSL of running VM
  - All sensitive instructions obtain info from VMPSL or trap to VMM, which emulates instruction



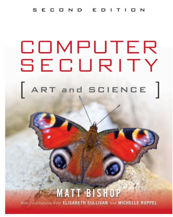
Virtualization Mode

- Intel VT-i adds PSR.vm bit to process status register
  - When running guest OS, bit set; else bit cleared
  - When set, privileged instructions cause virtualization fault
    - Bit automatically cleared so VMM can service it
- Intel VT-x adds 2 modes, root and non-root operation
  - When running guest OS, in VMX non-root operation
  - Privileged instructions cause transition to VMX root mode
    - Then VMM carries out privileged instruction



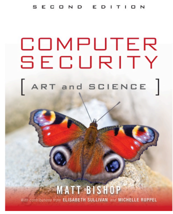
Access by Class

- Divide users into different classes
  - Control access to system by limiting access of each class
- Example: IBM VM/370 associates various commands with users
  - Each command associated with *user privilege classes*
    - Class G ("general user") can start VM
    - Class A ("primary system operator") can control system accounting, availability of VMs, etc.
    - Class "Any" can access, relinquish access, to VM



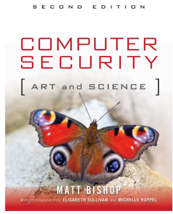
Physical Resources and VMs

- VMM distributes these among VMs as appropriate
- Example: minidisks
  - System to run 10 VMs using one disk
  - Split disk into 10 minidisks
  - VMM handles mapping from (virtual) minidisk address to physical disk address



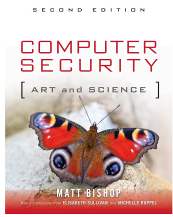
Example

- VM’s OS tries to write to a disk
  - Privileged I/O instruction causes trap to VMM
  - VMM translates address in I/O instruction to address in physical disk
  - VMM checks that physical address in area of disk allocated to the VM making request
    - If not, request fails; error returned to VM
  - VMM services request, returns control to VM



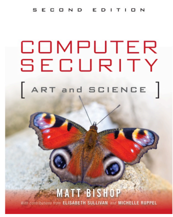
Paging and VM

- Paging on ordinary machines is at highest privilege level
- Paging on VM is at highest virtual level
  - Handled like any other disk I/O
- Two problems:
  - On some machines, some pages available only from highest privilege level, but VM runs at next-to-highest level
  - Performance



First Problem

- VM must change protection level of pages available only from highest privilege level to appropriate level
- Example:
  - On VAX/VMS, kernel mode needed for some pages
  - But VM runs at executive mode, so must ensure only virtual kernel level processes can read those pages
  - In practice, VMS system allows executive mode processes to elevate to kernel mode; no security issue
  - But … executive mode processes on non-VM system cannot read pages, so loss of reliability



Second Problem

- VMM paging is transparent to VMs
- VMs paging: VMM handles it as above
  - If lots of VM paging, this may cause significant performance degradation
- Example: IBM VM/370
  - OS/MFT, OS/MVT access disk storage
    - If jobs depend on timings, delays caused by VMM may affect results
  - MVS does that and pages, too
    - Jobs depending on timings could fail under VM/370 that would succeed if run under MVS directly