ADVANCED TOPICS: VIRTUAL MACHINES

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CS 537, Fall 2024

Administrivia

Project 5 happened?

Project 6 – last project!

- Early deadline this week!
- Final deadline end of next week

Shivaram office hours

- TODAY at 1pm!

AGENDA / LEARNING OUTCOMES

How to virtualize a machine underneath the OS?

PERSISTENCE RECAP

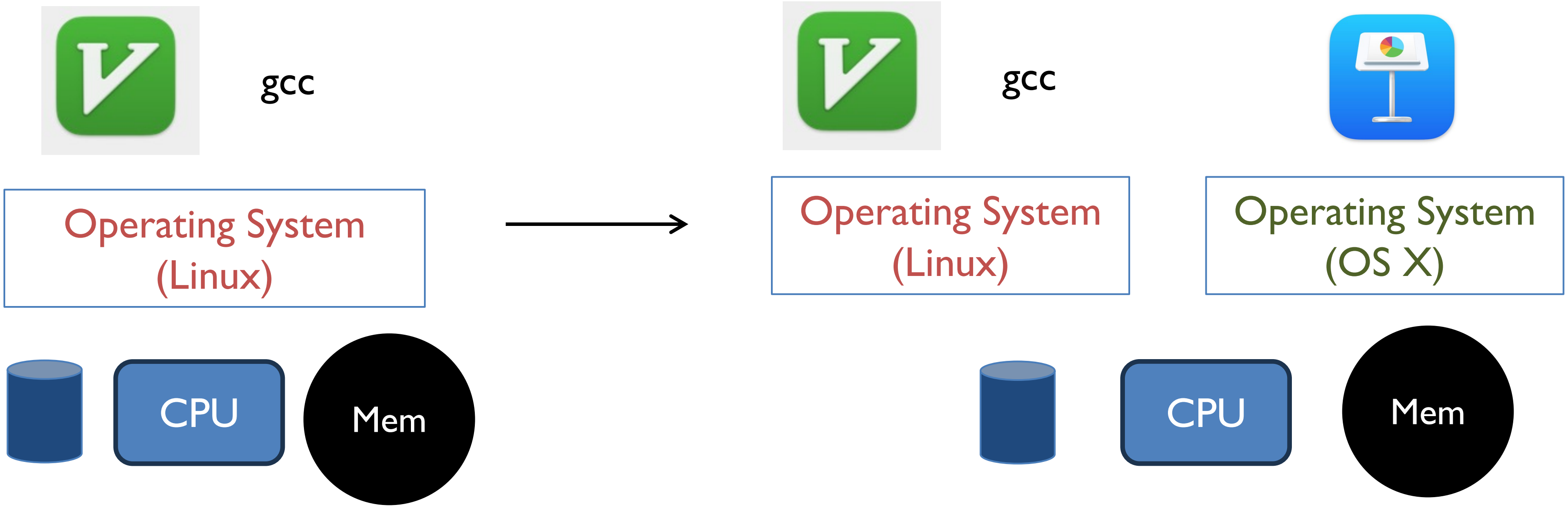
- Managing I/O devices significant part of OS
- Disk Drives, SSDs (pages, blocks)

- File Systems: OS provided API to access disk
- Simple FS: FS layout with supberblock, bitmaps, inodes, datablocks

- Fast File System: Key idea – put inode & data close together, namespace locality
- FSCK, Journaling – Handling/Preventing data inconsistencies

- Log Structured File System - Organize data based on writes

VIRTUAL MACHINES



VIRTUAL MACHINE USE CASES

Share mainframe systems (1970s)

Cloud Computing

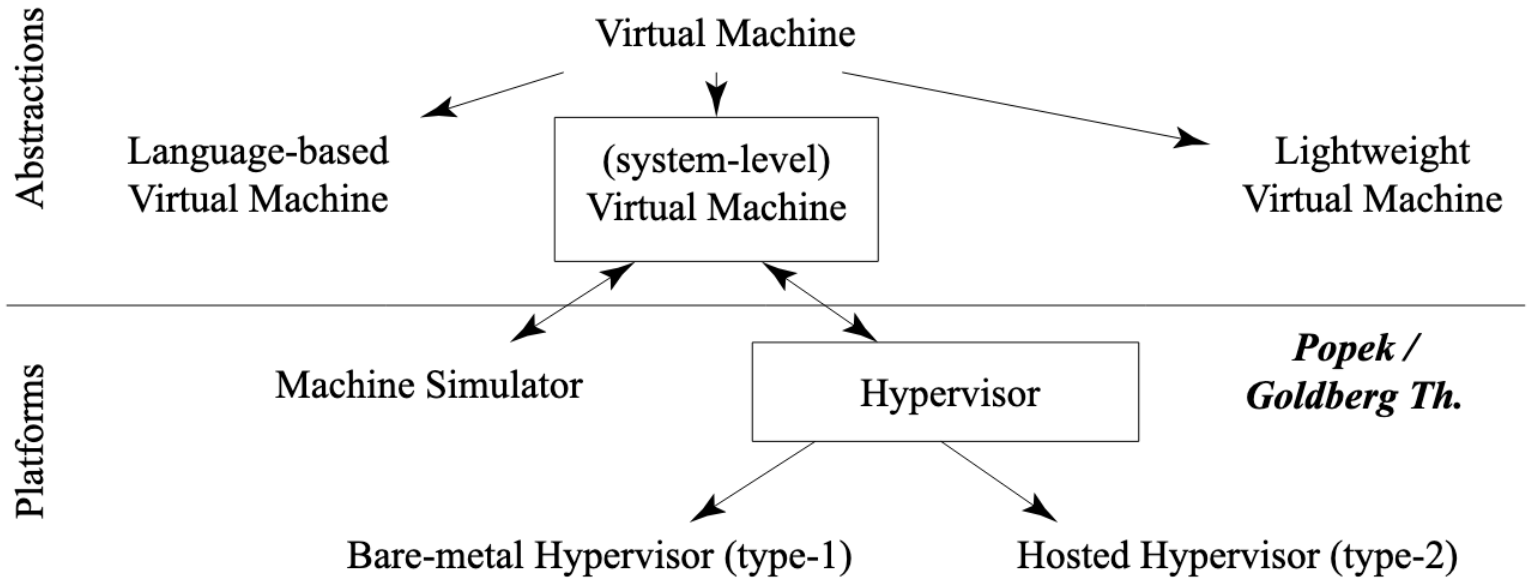
- Consolidate multiple tenants running different OS
- Strong Isolation

Run applications that only exist for specific OS

Testing, Debugging

DEFINITIONS

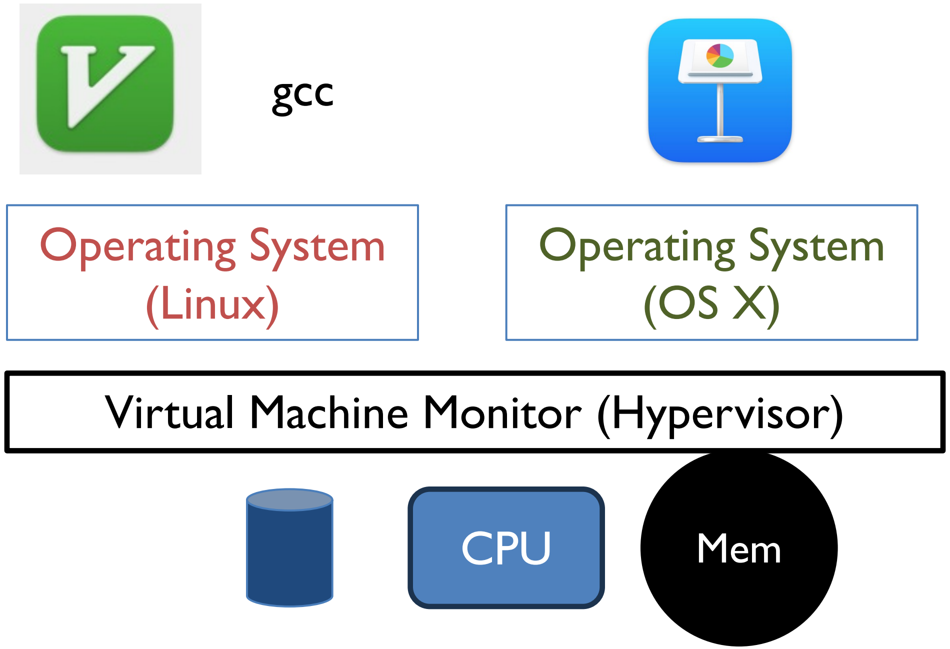
A virtual machine is a complete compute environment with its own isolated processing capabilities, memory, and communication channels.



VIRTUAL MACHINE MONITORS

Bare-metal Hypervisor (type-1)
direct control of all resources

Hosted Hypervisor (type-2)
operates as part of or on top of an existing host OS



GOALS

- Equivalence – The exposed resource is equivalent with the underlying computer.
- Safety – Isolation requires that the virtual machines are isolated from each other as well as from the hypervisor.
- Performance – The virtual system must show at worst a minor decrease in speed.

CAN WE VIRTUALIZE? (POPEK GOLDBERG 1974)

The processor's system state, called the processor status word (PSW) consists of the tuple (M, B, L, PC):

the execution level M = {s, u} (superuser or user mode)
the segment register (B,L); (Segmented Memory Model) and
the current program counter (PC), a virtual address

A virtual machine monitor may be constructed if the set of sensitive instructions for a computer is a subset of the set of privileged instructions.

$$\{control\text{-}sensitive\} \cup \{behavior\text{-}sensitive\} \subseteq \{privileged\}.$$

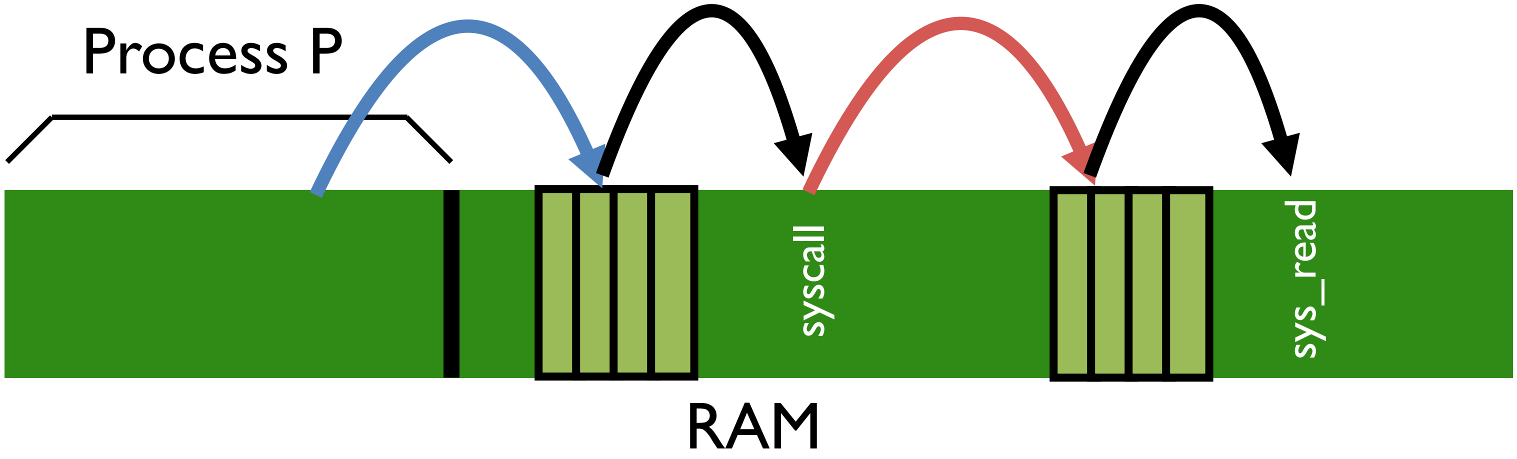
VIRTUALIZING THE CPU

Limited Direct Execution

How to handle privileged instructions (e.g., traps for system calls) ?

Trap and Emulate!

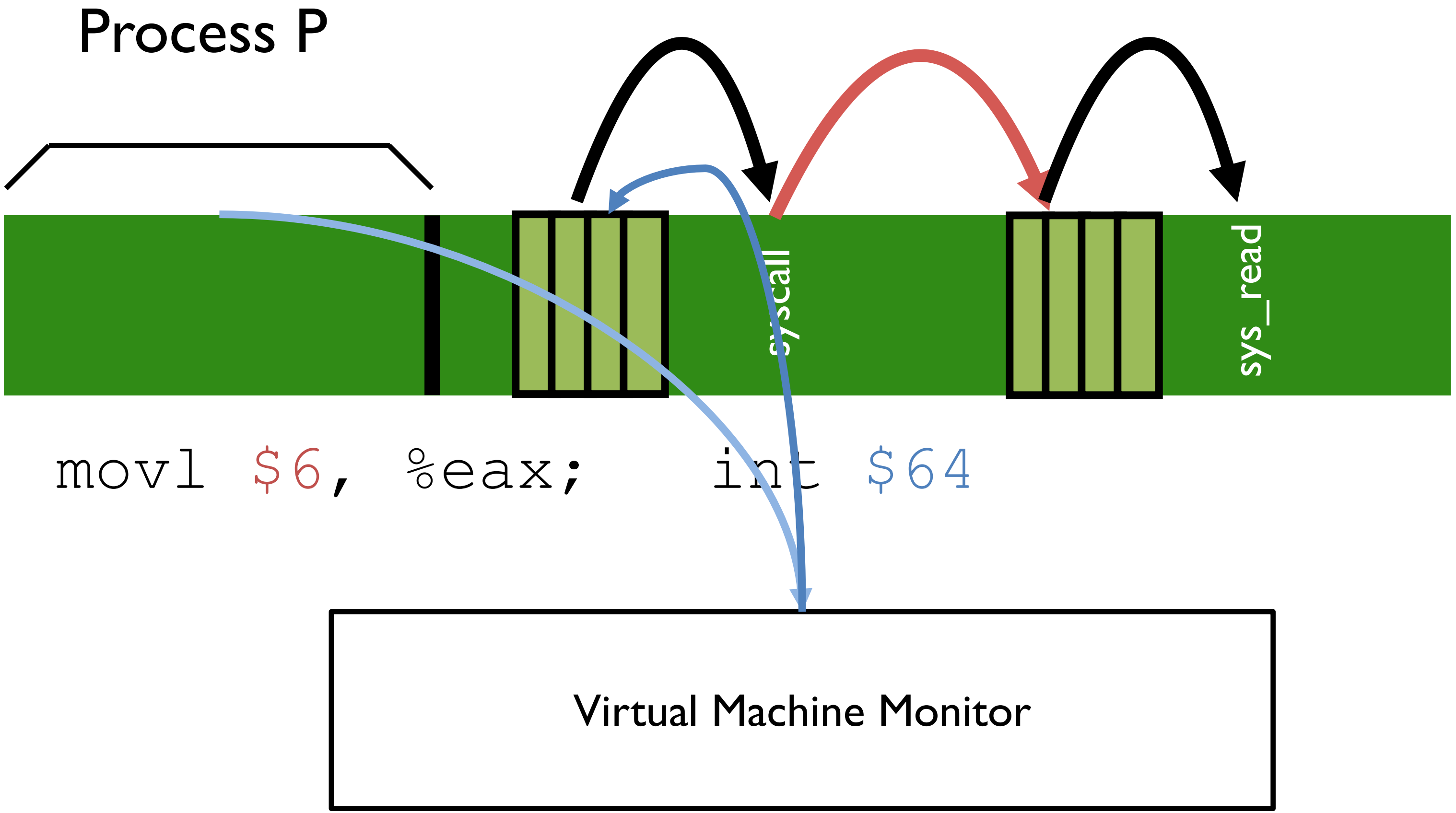
BEFORE: SYSTEM CALL FLOW




```
movl $6, %eax;    int $64
```

Transfer control to trap handler. Execute appropriate syscall routine

NEW: SYSTEM CALL



USER MODE, KERNEL MODE?

MIPS architecture:

- Guest OS runs in “supervisor” mode
- No privileged instructions, some extra memory

Run Guest OS in user mode

How to protect Guest OS data structures?

QUIZ 20

Log structured SSD consisting of 3 blocks and 10 pages per block. Each page holds a single character.

The state of each page (i, v, or E), the data stored at each page, and an indicator if a page is currently live (i.e. has a mapping in the FTL).

- read(page#) -- if page is live returns the character at the page, otherwise error
- write(page#,char) -- writes character to logical page #
- erase(page#) -- removes logical page # from the FTL mapping

```
FTL     0: 15   2: 18   3:  8   4:  4
       14: 16
Block 0          1          2
Page  0000000000 1111111111 2222222222
      0123456789 0123456789 0123456789
State vvvvvvvvvv vvvvvvvvvE iiiiiiiiii
Data  c9XhFAp970 CqFuArsJE
Live      +   +       ++ +


FTL     0: 15   2: 18   3:  8   4: 19
       14: 16
Block 0          1          2
Page  0000000000 1111111111 2222222222
      0123456789 0123456789 0123456789
State vvvvvvvvvv vvvvvvvvvv iiiiiiiiii
Data  c9XhFAp970 CqFuArsJEt
Live          +       ++ ++
```

If a write(0,'q') is now performed by the OS on the SSD state from the last question, what underlying SSD operations must be performed in order to accomplish this write?

```
FTL     0: 15   2: 18   3:  8   4: 19
       14: 16
Block 0          1          2
Page  0000000000 1111111111 2222222222
      0123456789 0123456789 0123456789
State vvvvvvvvvv vvvvvvvvvv iiiiiiiiii
Data  c9XhFAp97O CqFuArsJEt
Live          +       ++ ++
```

```
FTL     0: 15   2: 18   3:  8   4:  4
       14: 16
Block 0          1          2
Page  0000000000 1111111111 2222222222
      0123456789 0123456789 0123456789
State vvvvvvvvvv vvvvvvvvvE iiiiiiiiii
Data  c9XhFAp97O CqFuArsJE
Live      +   +        ++ +
```

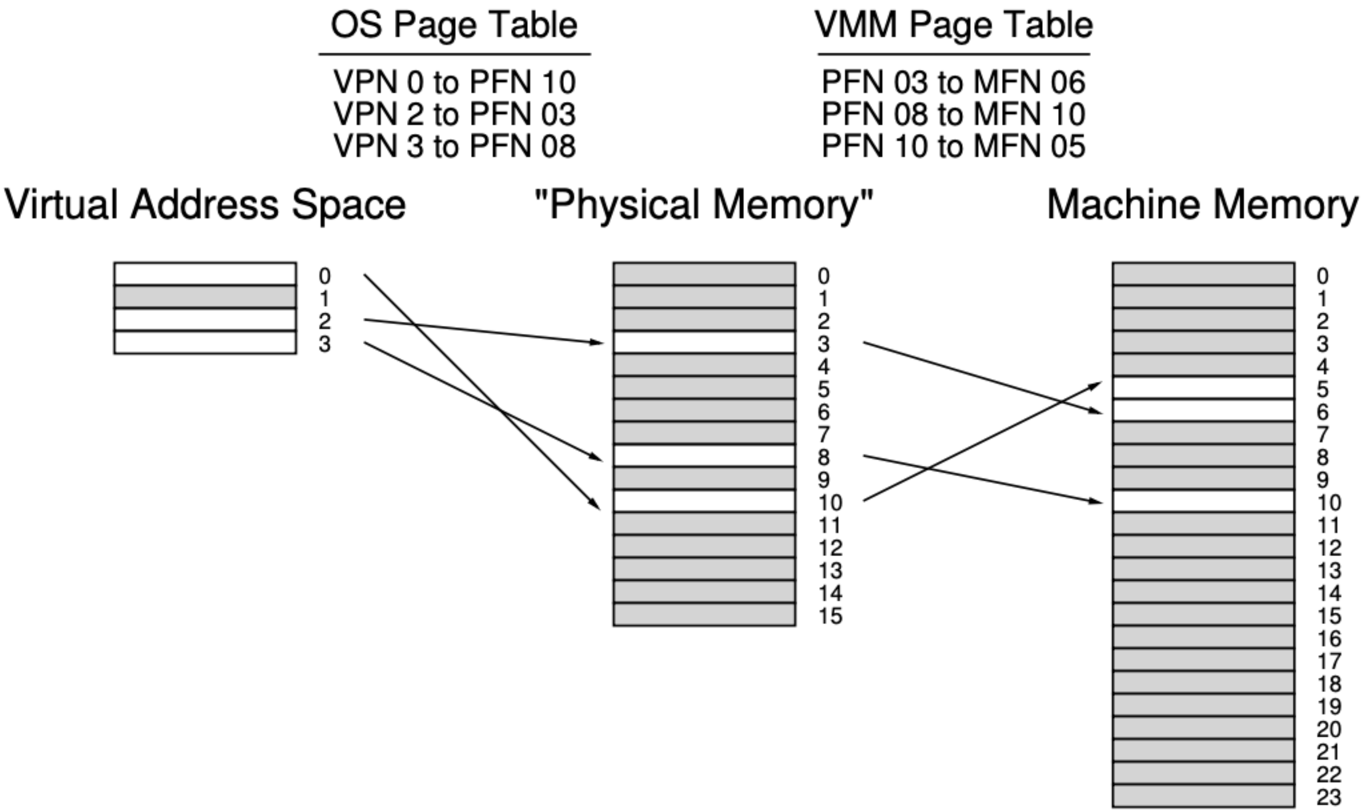
```
FTL     0: 15   2: 18   3: 21   4:  20
       14: 16
Block 0          1          2
Page  0000000000 1111111111 2222222222
      0123456789 0123456789 0123456789
State EEEEEEEEEE vvvvvvvvvE vvEEEEEEEE
Data             CqFuArsJE  F7
Live                   ++ +  ++
```

VIRTUALIZING MEMORY

Challenge: Who manages physical memory allocation?

How do we share physical memory across Guest OSes?

Extra level of indirection!



BEFORE: SOFTWARE TLB HANDLER

TLB miss in hardware

Trap into OS
OS walks pagetable
Get Virtual→Physical
Update TLB using privileged instruction

NEW: SOFTWARE TLB HANDLER

TLB miss

Trap into VMM
Call OS Handler

OS walks pagetable
Get Virtual→Physical
Update TLB using privileged instruction

Trap handler
Physical → Machine
Update TLB

TLB MISS OVERHEADS

Extra trap into VMM for Physical → Machine mapping

Avoid using Software "TLB" in VMM to cache Virtual → Physical

Hardware managed TLBs

- VMM maintains Shadow page table per of Virtual → Machine
- Trap when OS tries to update PTE (e.g., lcr3)

SO, CAN WE VIRTUALIZE X86?

Table 2.2: List of sensitive, unprivileged x86 instructions

Group	Instructions
Access to interrupt flag	pushf, popf, iret
Visibility into segment descriptors	lar, verr, verw, lsl
Segment manipulation instructions	pop <seg>, push <seg>, mov <seg>
Read-only access to privileged state	sgdt, sldt, sidt, smsw
Interrupt and gate instructions	fcall, longjump, retfar, str, int <n>

PARA VIRTUALIZATION, X86 EXTENSIONS

So far: No change to the guest OS. No changes to the hardware.

Downside: Overheads can be quite high?

Para virtualization

Can we make (small?) modifications to the guest OS for efficiency?

Hardware

Instruction set extensions (Intel, AMD)

XEN

Modify guest OS: simply undefine all of the 17 non-virtualizable instructions!

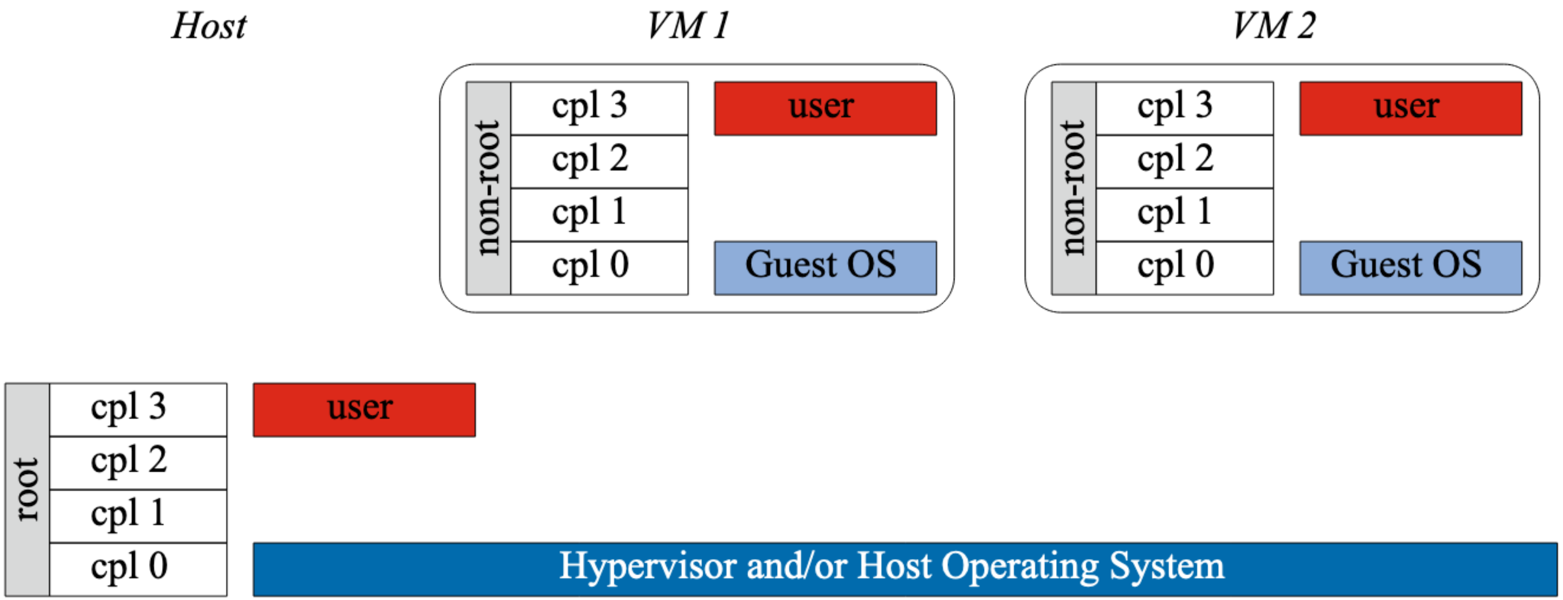
Alternate interrupt architecture

	Memory Management
Segmentation	Cannot install fully privileged segment descriptors and cannot overlap with the top end of the linear address space.
Paging	Guest OS has direct read access to hardware page tables, but updates are batched and validated by the hypervisor. A domain may be allocated discontinuous machine (aka host-physical) pages.
	CPU
Protection	Guest OS must run at a lower privilege level than Xen.
Exceptions	Guest OS must register a descriptor table for exception handlers with Xen. Aside from page faults, the handler remains the same.
System calls	Guest OS may install a “fast” handler for system calls, allowing direct calls from an application into its guest OS and avoiding indirection through Xen on every call.

INTEL VT-X EXTENSIONS

True Hardware Support meeting Popek / Goldberg Criteria
Do not change the semantics of individual instructions, instead duplicate the entire visible state and introduce a new mode of execution: the root mode.

- Hypervisor is in root mode, Guest OS in non-root mode.
- Special new instructions for detecting mode (only available in root mode, otherwise a trap is caused).
- New mode only used for virtualization
- Each mode has own address space
- Each mode has own interrupt flag


Host
VM 1
VM 2
non-root
cpl 3
cpl 2
cpl 1
cpl 0
user
Guest OS
non-root
cpl 3
cpl 2
cpl 1
cpl 0
user
Guest OS
root
cpl 3
cpl 2
cpl 1
cpl 0
user
Hypervisor and/or Host Operating System

Next class: Multi-CPU scheduling

Thanksgiving break!