L6: Operating Systems Structures

Sam Madden
madden@csail.mit.edu
6.033 Spring 2014

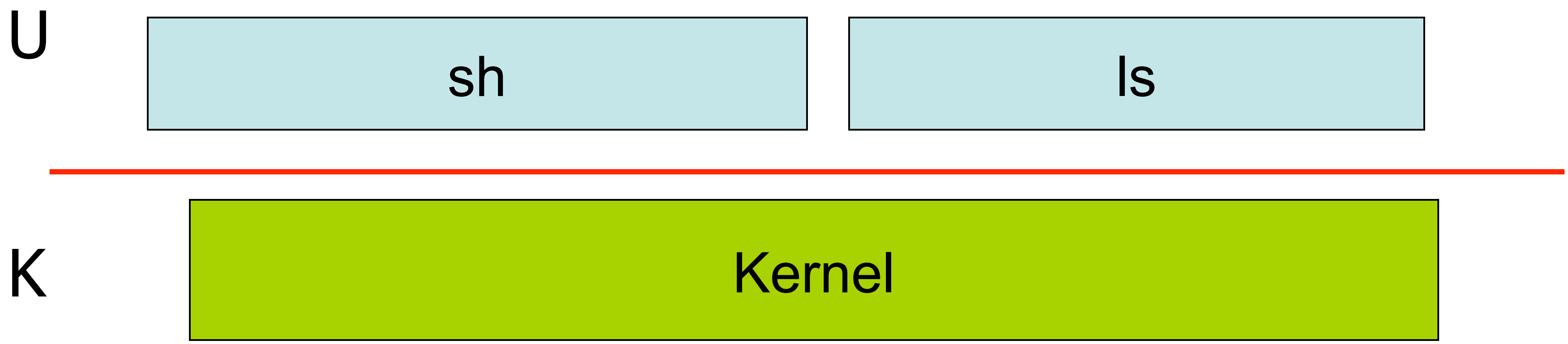
Overview

- Theme: strong isolation for operating systems
- OS organizations:
  - Monolithic kernels
  - Microkernel
  - Virtual machines

OS abstractions

- Virtual memory
- Threads
- File system
- IPC (e.g., pipes)
- …

Monolithic kernel (e.g., Linux)



- Kernel is one large C program
- Internal structure
  - E.g., object-oriented programming style
- But, no enforced modularity

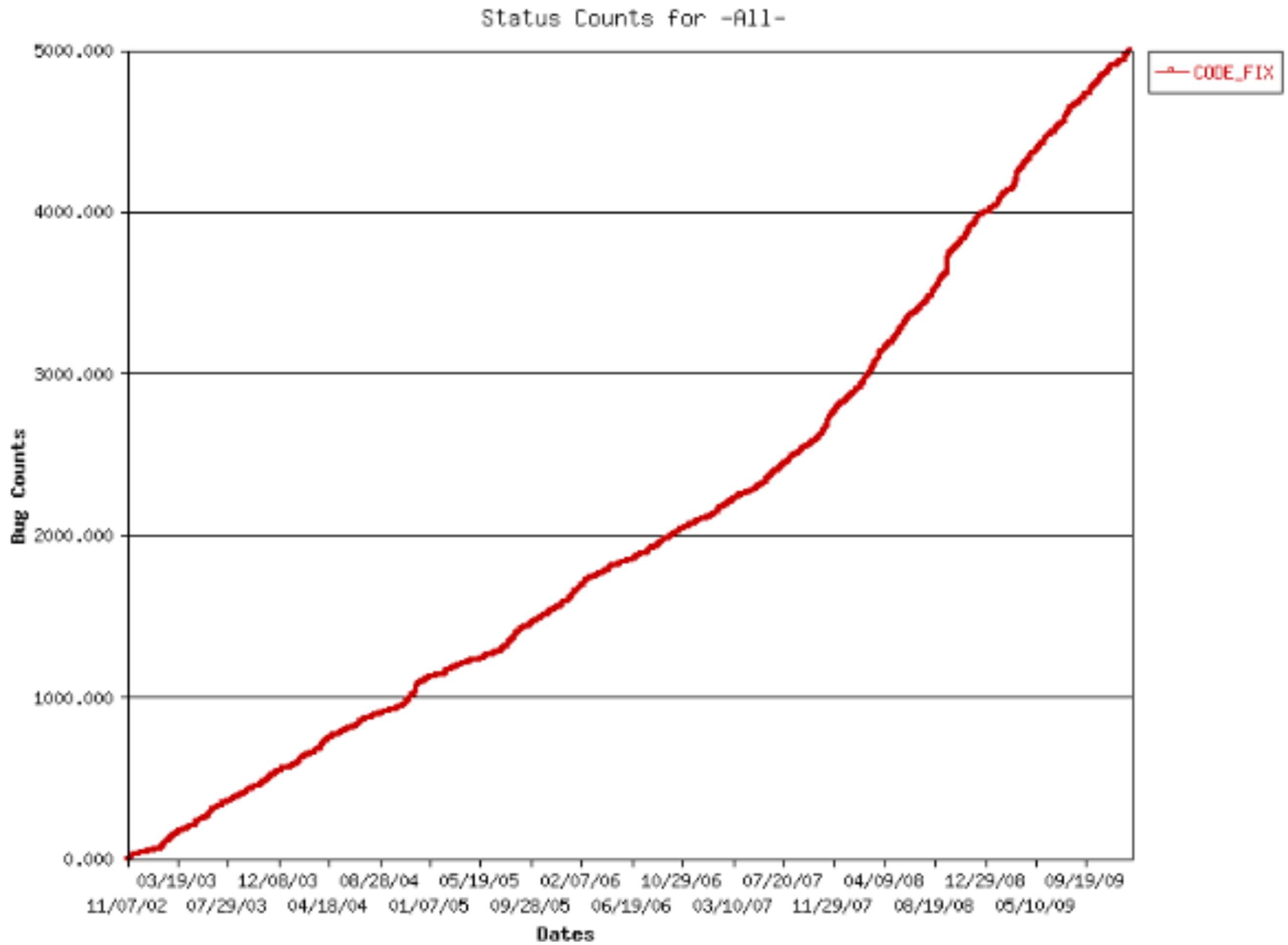
Kernel program is growing

- 1975 Unix kernel: 10,500 lines of code
- 2012: Linux 3.2

300,000 lines: header files (data structures, APIs)
490,000 lines: networking
530,000 lines: sound
700,000 lines: support for 60+ file systems
1,880,000 lines: support for 25+ CPU architectures
5,620,000 lines: drivers

9,930,000 Total lines of code

Linux kernel has bugs



5,000 bug reports fixed in ~7 years ➔ 2+ day

How bad is a bug?

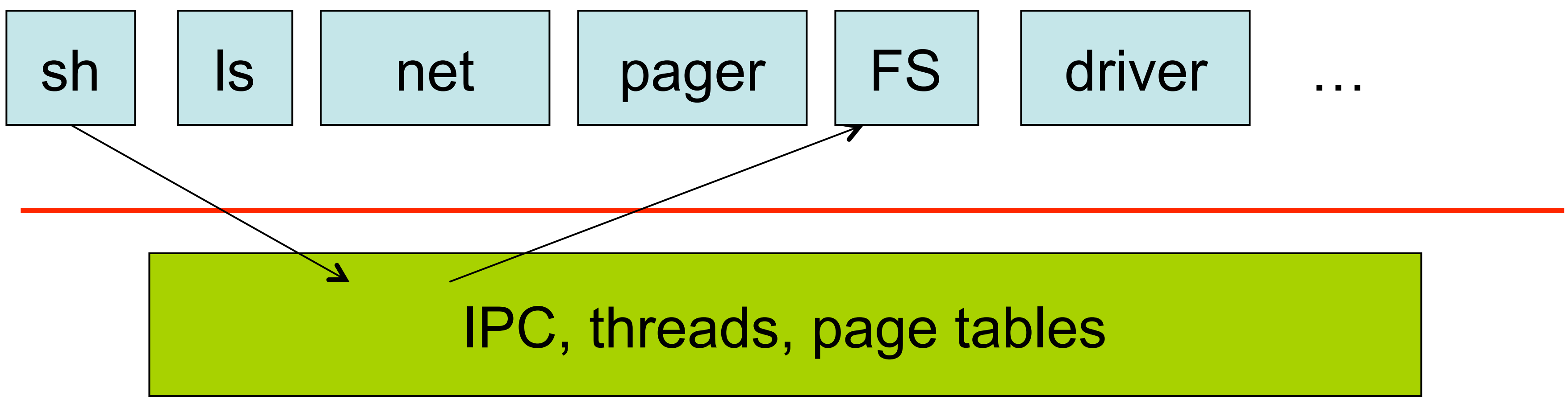
- Demo:
  - Insert kernel module
  - Every 10 seconds overwrites N locations in physical memory
  - N = 1, 2, 4, 8, 16, 32, 64, ….
- What N makes Linux crash?

Observations

- Linux lasts surprisingly long
- Maybe files were corrupted
- Every bug is an opportunity for attacker

- Can we enforce modularity within kernel?

Microkernel organization: Apply Client/Server to kernel



- User programs interact w. OS using RPC
- Examples: QNX, L4, Minix, etc.

Challenges

- Communication cost is high
  - Much higher than procedure call
- Isolating big components doesn’t help
  - If entire FS crashes, system unusable
- Sharing between subsystems is difficult
  - Share buffer cache between pager and FS

- Requires careful redesign

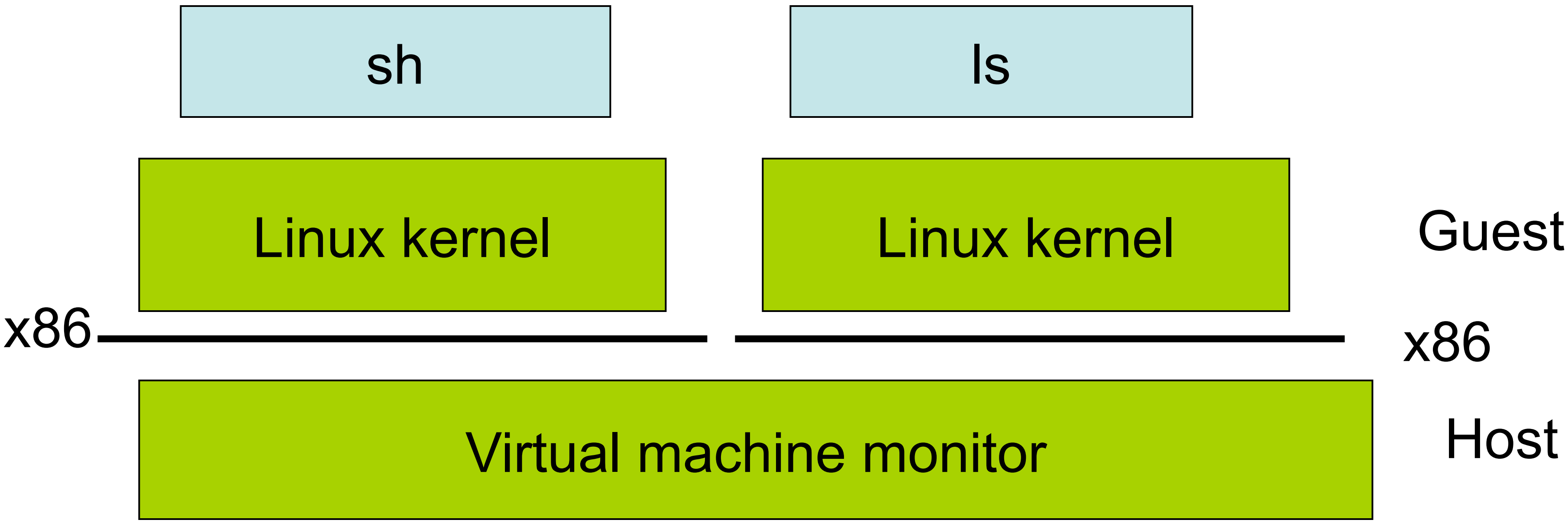
Why is Linux not a pure microkernel?

- Many dependencies between components
- Redesign is challenging
  - Trade-off: new design or new features?
- Some services are run as user programs:
  - X server, some USB drivers, SQL database, DNS server, SSH, etc.

Goal: isolation and compatibility

- Idea: run different programs on different computers
- Each computer has its on own kernel
  - If one crashes, others unaffected
  - Strong isolation
- But, cannot afford that many computers
  - Virtualization and abstraction ….
  - New constraint: compatibility

Approach: virtual machines



- Pure virtualization of hardware
  - CPU, memory, devices, etc.
- Provides strong isolation

How to implement VMM?

- One approach: pure emulation (e.g., QEMU)
  - VMM interprets every guest instruction

```
int32_t regs[8];
#define REG_EAX 1;
#define REG_EBX 2;
#define REG_ECX 3;
...
int32_t eip;
int16_t segregs[4];
...

char mem[256*1024*1024];
```

Emulation of CPU

```
for (;;) {
        read_instruction();
        switch (decode_instruction_opcode()) {
        case OPCODE_ADD:
                int src = decode_src_reg();
                int dst = decode_dst_reg();
                regs[dst] = regs[dst] + regs[src];
                break;
        case OPCODE_SUB:
                int src = decode_src_reg();
                int dst = decode_dst_reg();
                regs[dst] = regs[dst] - regs[src];
                break;
        ...
        }
        eip += instruction_length;
}
```

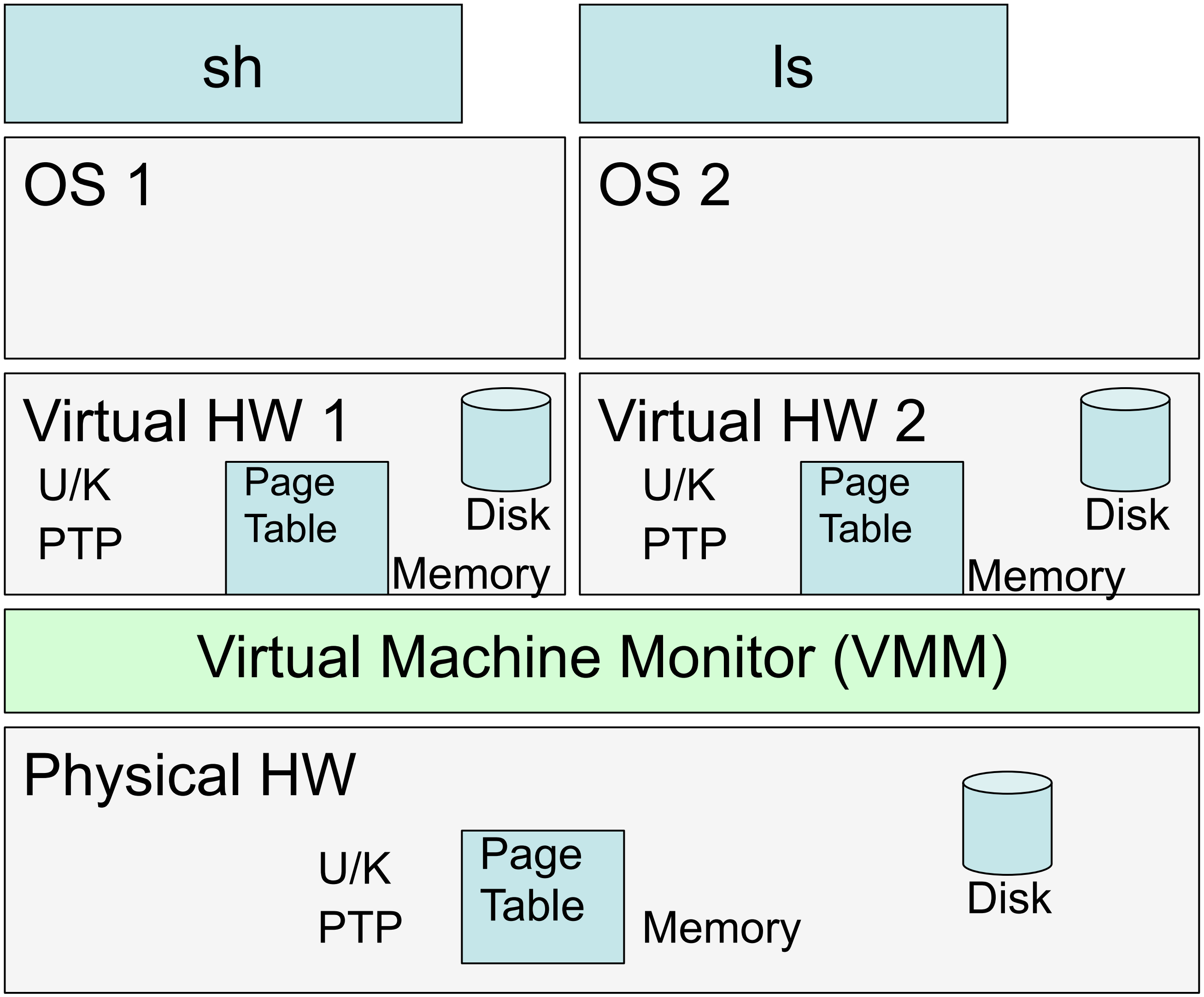
Goal: “emulate” fast

- Observation: guest instructions are same has hardware instructions
- Idea: run most instructions directly
  - Fine for user instructions (add, sub, mul)
  - But not for, e.g., privileged instructions
  - What hardware state must be virtualized to run several existing kernel?

Kernel virtualization

- Each kernel assumes its manages:
  - Physical memory
  - Page-table pointer
  - U/K bit
  - Interrupts, registers, etc.
- How to virtualize these?

Virtual Machines



Need to virtualize:

1. **memory**
2. **U/K bit**
3. **disk**

Memory virtualization

- Idea: an extra level of page tables

Guest virtual address

Kernel page table

Guest physical addresses

VMM page table

Host physical addresses

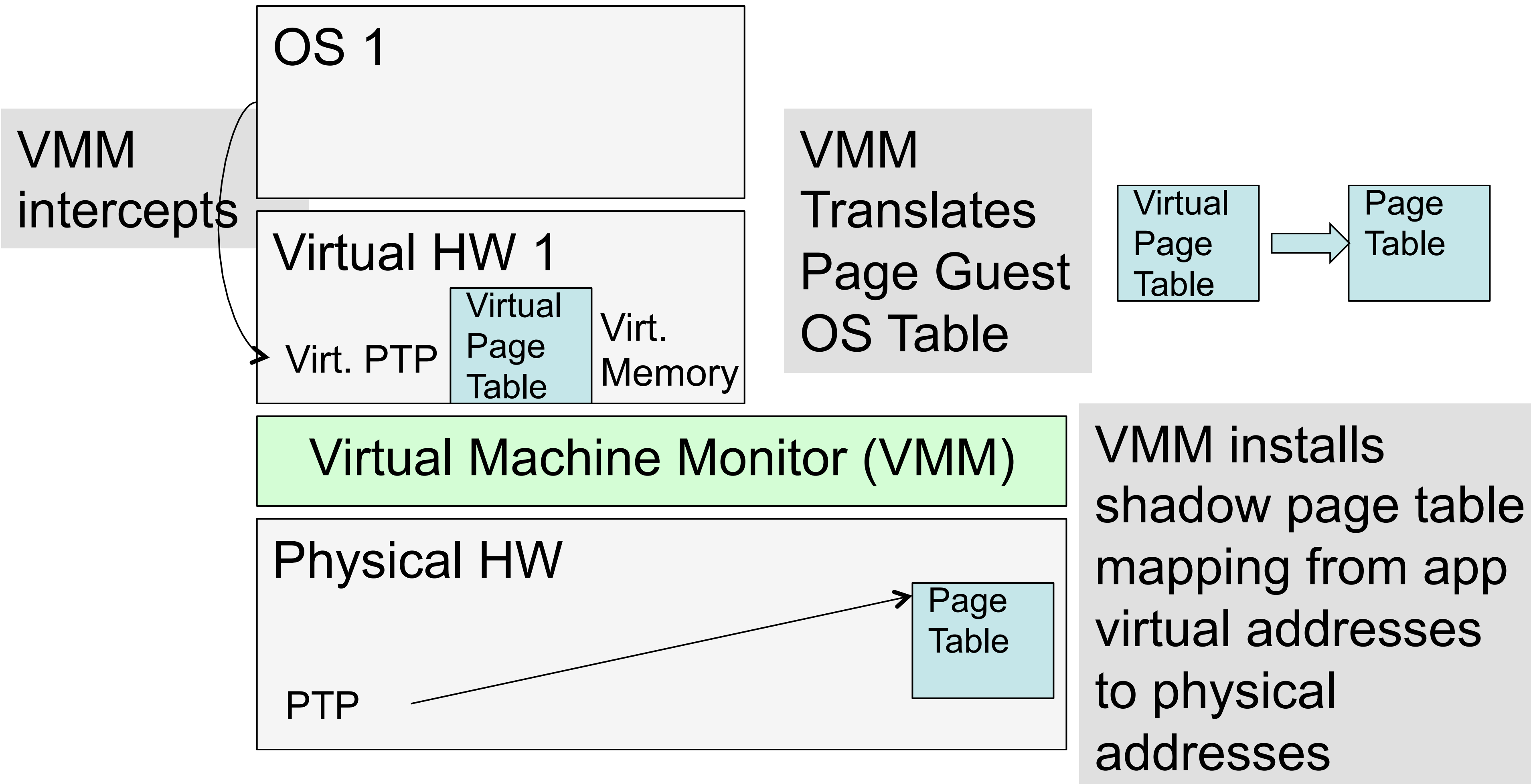
Virtualizing page table pointer

- Guest OS cannot load PTP
  - Isolation violated
  - Guest OS will specify guest physical addresses
    - Not an actual DRAM location

A solution: shadow page tables

- VMM intercepts guest OS loading PTP
- VMM iterates over guest PT and constructs shadow PT:
  - Replacing guest physical addresses with corresponding host physical addresses
- VMM loads host physical address of shadow PT into PTP

Shadow Page Tables



Translating Page Tables

VMM Page Table

Guest PA	PA
0xA1	0xC0
0xA2	0xC1
0xA3	0xC4

Maps from guest physical address to real physical addresses

Guest OS Page Table

VA	Guest PA
0x01	0xA2
0x02	0xA3

Maps app virtual addresses to guest physical addresses

Real Page Table

VA	PA
0x01	0xC1
0x02	0xC4

Maps app virtual addresses to real physical addresses

Computing shadow PT

31 12	11 9	8	7	6	5	4	3	2	1	0
Physical-Page Base Address	AVL	G	P A T	D	A	P C D	P W T	U / S	R / W	P

```
compute_shadow_pt(guest_pt)
    For gva in 0 .. 2^20:
        if guest_pt[gva] & PTE_P:
                gpa = guest_pt[gva] >> 12
                pa = vmm_pt[gpa] >> 12
                shadow_pt[gva] = (pa << 12)| PTE_P
        else:
                shadow_pt[gva] = 0
```

PTE_P = page is present

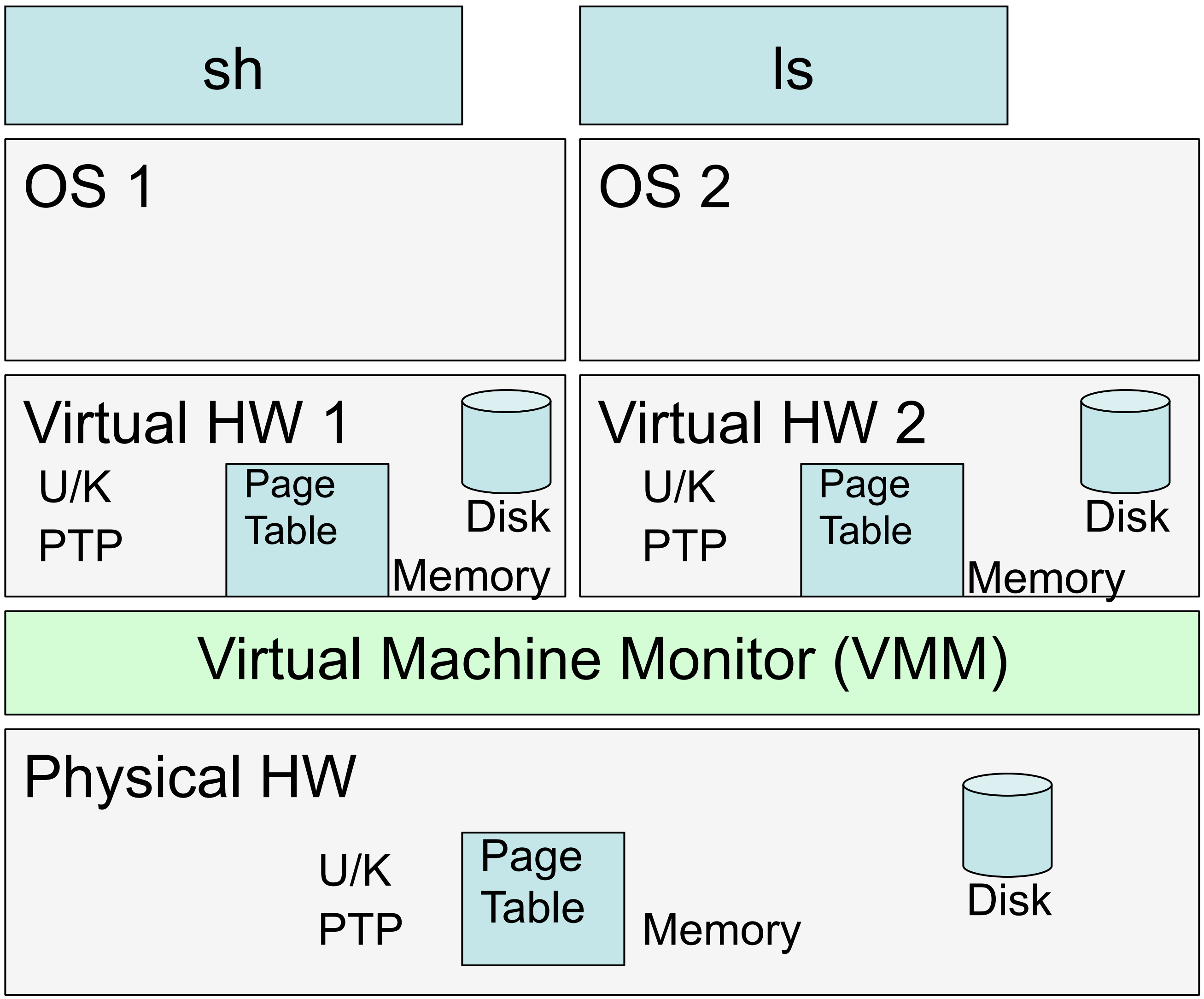
Computing shadow PT

31–12	11–9	8	7	6	5	4	3	2	1	0
Physical-Page Base Address	AVL	G	PAT	D	A	PCD	PWT	U/S	R/W	P

```
compute_shadow_pt(guest_pt)
    For gva in 0 .. 2^20:
        if guest_pt[gva] & PTE_P:
                gpa = guest_pt[gva] >> 12
                pa = vmm_pt[gpa] >> 12
                shadow_pt[gva] = (pa << 12)| PTE_P
        else:
                shadow_pt[gva] = 0
```

R/W = page is read only

Virtual Machines



Need to virtualize:

1. **memory**
2. **U/K bit**
3. **disk**

Guest modifies its PT

- Host maps guest PT *read-only*
- If guest modifies, hardware generates page fault
- Page fault handled by host:
  - Update shadow page table
  - Restart guest

Virtualizing U/K bit

- Hardware U/K bit must be U when guest OS runs
  - Strong isolation
- But now guest cannot:
  - Execute privileged instructions
  - …

A solution: trap-and-emulate

- VMM stores guest U/K bit in some location
- VMM runs guest kernel with U set
- Privileged instructions will cause an exception
- VMM emulates privileged instructions, e.g.,
  - Set or read virtual U/K
  - if load PTP in virtual K mode, load shadow page table
  - Otherwise, raise exception in guest OS

Hardware support for virtualization

- AMD and Intel added hardware support
  - VMM operating mode, in addition to U/K
  - Two levels of page tables
- Simplifies job of VMM implementer:
  - Let the guest VM manipulate the U/K bit, as long as VMM bit is cleared.
  - Let the guest VM manipulate the guest PT, as long as host PT is set.

Virtualizing devices (e.g., disk)

- Guest accesses disk through special instructions:
- Trap-and-emulate:
  - Write “disk” block to a file in host file system
  - Read “disk” block from file in host file system

Benefits of virtual machines

- Can share hardware between unrelated services, with enforced modularity
  - “Server consolidation”
- Can run different operating systems
- Level-of-indirection tricks:
  - Snapshots
  - Can move guest from one physical machine to another

VMs versus microkernels

- Solving orthogonal problems
  - Microkernel: splitting up monolithic designs
  - VMs: run many instances of existing OS

Summary

- Monolithic kernels are complex, error-prone
  - But, not that unreliable …
- Microkernels
  - Enforce OS modularity with client/server
  - Designing modular OS services is challenging
- Virtual machines
  - Multiplex hardware between several operating systems