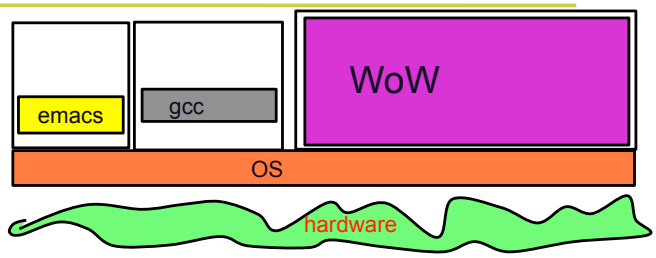
CS 140 – Summer 2008 – Handout #26: Virtual Machines

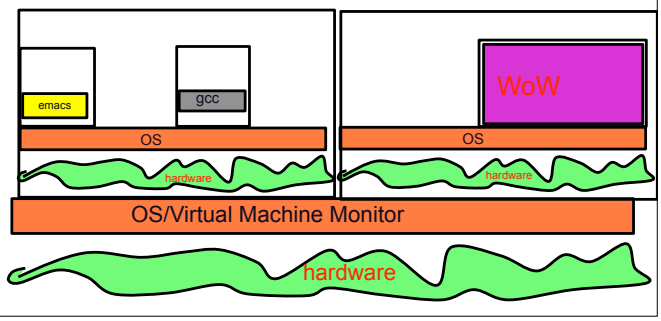
Review: What is an OS?



- Software between applications and (ugly) hardware:
  - **Abstracts hardware and makes portable, usable and pretty.**
  - **Makes finite into (near)infinite.**
  - **Provides protection.**

What If?

- Process abstraction looked just like hardware!



How is a process different from HW?

Process

- CPU – Non-Privileged registers and instructions.
- Memory – Virtual memory.
- Exceptions – signals, errors.
- I/O - File System, Directory, Files, raw devices.

Hardware

- CPU – All registers and instructions.
- Memory – Both virtual and physical memory, memory management, TLB/page tables, etc.
- Exceptions – Trap architecture, interrupts, etc.
- I/O – I/O devices accessed using programmed I/O, DMA, interrupts.

One way: Complete Machine Simulation

- Build a simulation of all the hardware.
  - **CPU – A loop that fetch an instruction, decode it, simulate its effect on the machine, state.**
  - **Memory – Physical memory is just an array, simulate the MMU on all memory accesses.**
  - **I/O – Simulate I/O devices, programmed I/O, DMA, interrupts.**
- Problem: Too slow!
  - **100x slowdown makes it not too useful.**
  - **CPU/Memory – 100x CPU/MMU simulation.**
  - **I/O Device – <2x slowdown.**
- Need to emulate CPU/MMU fast enough.

Dynamic Binary Translation

- Problem: simulated CPU, MMU not fast enough
  slow interpreter!
- Solution: translate & execute translated code

```
add r1, r2, r3
lw r4, 8(r1)
```

→

```
lea r4, REG_BASE
lw r2, R2_OFS(r4)
lw r3, R3_OFS(r4)
add r1, r2, r3
jal translate_r1
lw r1, 8(r1)
sw r1, R4_OFS(r4)
```

- Similar to just-in-time (JIT) compilation (e.g. Java, .net)
- ~4-10x slowdown (better if we can use hardware MMU?)
- Can we do better?

Making a process look like hardware - CPU

- Observations: Most instructions are the same regardless of processor privilege level.
  - **Example: `inc %eax`**
- Why not just let CPU execute the instructions directly?
  - **Safety – How we going to get it back? Or stop it from stepping on us? How about CLI/HALT?**
  - **Answer: Use protection mechanism.**
- Run virtual machine directly on CPU at non-privileged level.
  - **Most instructions just work.**
  - **Privileged instructions trap into monitor and run simulator on instruction.**
  - **Makes some assumptions about architecture.**

CPU Trap architecture virtualization

- What happens when an interrupt or trap occurs.
  - **Like all OSes: we trap into the monitor.**
- What if the interrupt or trap should go to the VM?
  - **Example: Page fault, illegal instruction, system call, interrupt.**
- Run the simulator again.
  - **X86 example: Lookup trap vector in VM's IDT.**
    - **Push `cs`, `eip`, `eflags`, on stack.**
    - **Switch to privileged mode.**

CPU Virtualization Requirements

- Need protection levels to run VMs and monitors
- All unsafe/privileged operations should trap
  - **Example: disable interrupt, access I/O dev, …**
  - **x86 problem: `POPF` (different semantics in different rings)**
- Privilege level should not be visible to software
  - **Software in VM should be able to query and find its in a VM**
  - **x86 problem: `MOV ax, cs`**
- Trap should be transparent to software in VM
  - **Software in VM should be able to tell if instruction trapped.**
  - **x86 problem: traps can destroy machine state.**
- Lost art
  - **Re-found - Intel's VT, AMD-V**

Possible solutions (w/o HW support)

- Modify the OS? (Xen, User-Mode Linux approach)
  - Change so it doesn't use non-virtualizable instructions.
  - In fact, can just call VMM directly – possibly more efficient!
  - Not general solution – can't run Windows.
- *Partial* binary translation (VMware approach)
  - Run user code directly.
  - Translate kernel code, patching non-virtualizable instructions
    - can also patch other instructions for performance!
  - As with DBT, need to track self-modifying code.
    - Map non-writable in MMU, trap & re-translate.
    - Windows does this. Also pages share code & data.
  - Have interpreter for code that is rarely used
    - avoid translation overhead

Virtualization Requirements - Virtualizing Memory

Basic MMU functionality used by OS:
- OS manages physical memory (0…MAX_MEM).
- OS sets up page tables mapping VA->PA.
- CPU accesses VA to should go to PA. Paging off: PA=VA.
- Used for every instruction fetch, load, or store.

Need to implement a *virtual* physical memory
- Logically need additional level of indirection
- VM's VA -> VM's PA -> machine address

Trick: Use hardware MMU to simulate virtual MMU.
- Can be folded into page tables: VA->machine address

MMU Virtualization

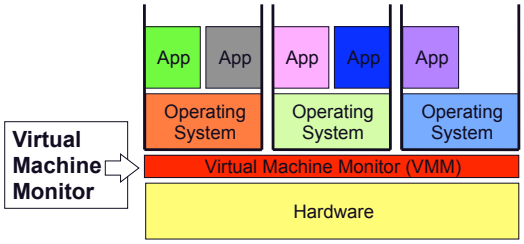
- Trick: Monitor keeps shadow of VM's page table
  - **Contains mapping to physical memory allocated for that VM.**
  - **Access causes Page Fault:**
    - **Lookup in VM's page table mapping from VPN to PPN.**
    - **Determine where PPN is in machine memory (MPN).**
      - Monitor can demand page the virtual machine
    - **Insert mapping from VPN->MPN into shadow page table.**
- Uses hardware for protection/isolation
  - **Monitor never maps itself into VM's page table**
  - **Monitor never maps memory allocated to other VMs in VM's page table**
- AMD's Nested Page Tables

I/O device virtualization

- Type of communication:
  - **Special instruction – IN/OUT.**
  - **Memory mapped I/O (PIO).**
  - **Interrupts.**
  - **DMA.**
- Virtualization
  - **Make IN/OUT and PIO trap into monitor.**
  - **Run simulation of I/O device.**
- Simulation:
  - **Interrupt – Tell CPU simulator to generate interrupt.**
  - **DMA – Copy data to/from physical memory of virtual machine.**

Virtual Machine Monitor

- Thin layer of software that virtualizes the hardware
  - **Exports a virtual machine abstraction that looks like the hardware.**



Old idea from the 1960s

- IBM VM/370 – A VMM for IBM mainframes
  - **Multiplex multiple OS environments on expensive hardware.**
  - **Desirable when few machines around.**
  - **Also: make single-user OS "multi-user."**
- Interest died out in the 1980s and 1990s.
  - **Hardware got cheap (with faster CPUs, huge mem/storage.)**
  - **Compare Windows XP vs. *N* DOS machines**
    - **However, Windows includes a DOS virtual environment. ;-)**
- Interesting again today
  - **Different problems today – software management**
  - **VMM attributes still relevant**

Virtual Machine Monitor attributes

- Software compatibility
  - **Runs pretty much all software**
  - **Trick: Make virtual hardware match real hardware.**
- Low overheads/High performance
  - **Near "raw" machine performance.**
  - **Direct execution on CPU/MMU.**
- Complete isolation
  - **Total data isolation between virtual machines.**
  - **Use hardware protection.**
- Encapsulation
  - **Virtual machines are not tied to physical machines.**
  - **Checkpoint/Migration.**

Different thinking about OSes

- Installing software on hardware is broken
  - **Tight coupling of OS and applications to hardware creates management problems.**
- Want to subdivide OS:
  - **Hardware drivers.**
  - **Hardware management.**
  - **System support software.**
- Turn OSes into normal software that can be managed

Backward compatibility with VMMs

- Backward compatibility is bane of new OSes.
  - **Huge effort require to innovate but not break.**
- Security considerations may make it impossible
  - **Choice: Close security hole and break apps or be insecure**
- Example: Not all XP applications run on Vista.
  - **In spite of a *huge* effort to make Vista compatible.**
  - **Given the number of applications that run on XP, practically any change will break something.**
    - **If (OS == XP)….**
- Solution: Use a VMM to run both XP and Vista
  - **Obvious for OS migration as well: Windows -> Linux**
  - **keep running legacy apps, OS until you can replace them on new OS**

Isolation: access to classified networks

- Traditional tension: Security vs. Usability
  - **Secure systems tend not to be that usable.**
  - **Flexible systems are not that secure.**
- Additional information assurance requirement:
  - **Data cannot flow between networks of different classification.**
- Solution: Run two VMs:
  - **Classified VM**
  - **Internet VM**
- Use isolation property to isolate two VMs
  - **VMM has control of the information flow between machines**
    - **Declassifier mechanism**

Logical partitioning of server machines

- Run multiple servers on same box
  - **Ability to give away less than one machine.**
    - **Modern CPUs more power than most services need.**
  - **0.10U rack space machine - Better power, cooling, floor space,etc.**
  - **Server consolidation trend: N machine -> 1 real machine.**
- Isolation of environments
  - **Printer server doesn't take down Exchange server.**
  - **Compromise of one VM can't get at data of others.**
- Resource management
  - **Provide service-level agreements.**
- Heterogeneous environments
  - **Linux, FreeBSD, Windows, etc.**

Example: Using VMM to enhance security

- Problem Area: Intrusion Detection Systems (IDS).
- Trade-offs
  - Host-based IDS (HIDS):
    - + Good visibility to catch intruder.
    - - Weak isolation from intruder disabling/masking IDS.
  - Network-based IDS (NIDS):
    - + Good isolation from attack from intruder.
    - - Weak visibility can allow intruder to slip by unnoticed.
- Would like visibility of HIDS with isolation of NIDS.
  - Idea: Do it in the virtual machine monitor.

VMM-based Intrusion Detection System

- Strong isolation
  - VMM isolate software in VM from VMM.
  - Comprise OS in VM can't disable IDS in VMM.
- Introspection – Peer inside at software running in VM
  - VMM can see: Physical memory, registers, I/O device state, etc.
  - Signature scan of memory
    - Look through physical memory for patterns or signs of break-in
- Interposition – Modify VM abstraction to enhance security
  - Memory Access Enforcer
    - Interpose on page protection.
  - NIC Access Enforcer
    - Interpose on virtual network device.

Virtual Appliances

- Virtualization decouples software from hardware
  - OS no longer an extension of hardware
- OS is bundled with application
  - Choose OS based on the needs of the application
  - only include what you need
- No additional installation required
  - VM includes OS, libraries, application, support software
  - No hardware incompatibilities (runs on virtual hardware)
  - No software incompatibilities (includes entire environment)
- "Virtual Appliance"
  - web server, mail server, standard desktop, test environment...
  - tons of them available on internet

Mobility

- Virtual machines allow you to push nodes around on your network
  - as long as network can route/switch seamlesly
- Move servers around to optimize for
  - performance (few VMs per machine)
  - power, hardware resources (many VMs per machine)
  - network latency (put VMs close to clients)
- Keep your work on a VM, and take it with you!
  - beyond afs home directory – get your whole *machine*
  - log into a machine – loads *your* VM
  - put it on a flash drive, send it over the network...

Live upgrades

- Can upgrade hardware, VMM while OS and applications continue to run
  - move VMs off machine you're upgrading
  - upgrade/replace hardware and/or VMM
  - reboot and restart VMM
  - move VMs back
- Virtual machines make the OS much more flexible and useful, provide improved compatibility and isolation, and allow you to fix problems and limitations of a legacy OS!

Question: Has OS design failed?

- Microkernels
  - "A virtual machine monitor is a *µ*kernel with a lousy API."
  - Microkernels at same layer as VMM.
  - Never caught on – why? Performance, *compatibility.*
- Distributed (Operating) Systems
  - Merge systems over network into coherent whole.
  - Provide process migration, unified file system, etc.
  - Problems: performance, reliability, *compatibility.*
  - Future: IFC, network security, Web/Cloud/Grid computing?

Has OS design failed?

- OS libraries and software environments
  - Poor support for multiple (e.g. legacy) environments.
  - Destructive software installation. Poor *compatibility.*
- Security: OS design (and implementation) has failed!
  - Buy new laptop + connect to internet => pwned.
  - Viruses, worms, spyware, rootkits, spam, phishing, botnets, remote exploits, local privilege escalation, buffer overflows, TOCTTOU bugs, bad permissions, excessive privileges...
  - Result: poor isolation means people are (rightly) afraid to run e-mail and web server in same OS.
- VMMs offer a general workaround to OS deficiencies, by implementing an ugly (hardware) interface which OSes were supposed to make pretty and useful!

The Operating System
Traditional View

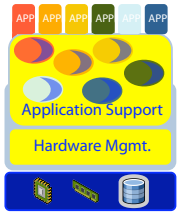
OS jobs:

1. Drive and manage hardware
2. Export better abstraction

OS is viewed as an extension of hardware

Privileged position – Only one OS

Modern OS Evolution

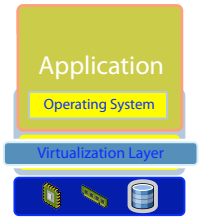


Goal – Support as many applications as possible

Problems – Too complex

- Security
- Reliability
- Manageability
- Performance
- Innovation

Virtual Appliance Operating System as evolution beyond traditional OS model



Don't need complex hardware management

Don't need broad application support

Application-specific operating system

Smaller, easier to get right!

Look at hardware appliance operating systems for examples

Living in a Virtual World

- Virtualization makes OS flexible, portable, controllable and (potentially) fixable without internal changes
- Black boxes now manipulable objects
  - OS, binary software, file systems, networks...
  - Crack open, modify, ship around, monitor, etc.
- More opportunities for OS developers!
  - Someone can run your custom OS (and keep Windows too)
  - Application-specific OSes
- ... with less importance per opportunity
  - OS doesn't matter as much
  - But now *you* know enough to hack VMMs as well as OSes!