Virtual Machine Monitors

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Talk Goal

- Understand the capabilities of Virtual Machine Monitors
  - What they can (and can't) do.

- Observation:

  Virtual machine monitor

  \+ Smart person with problem

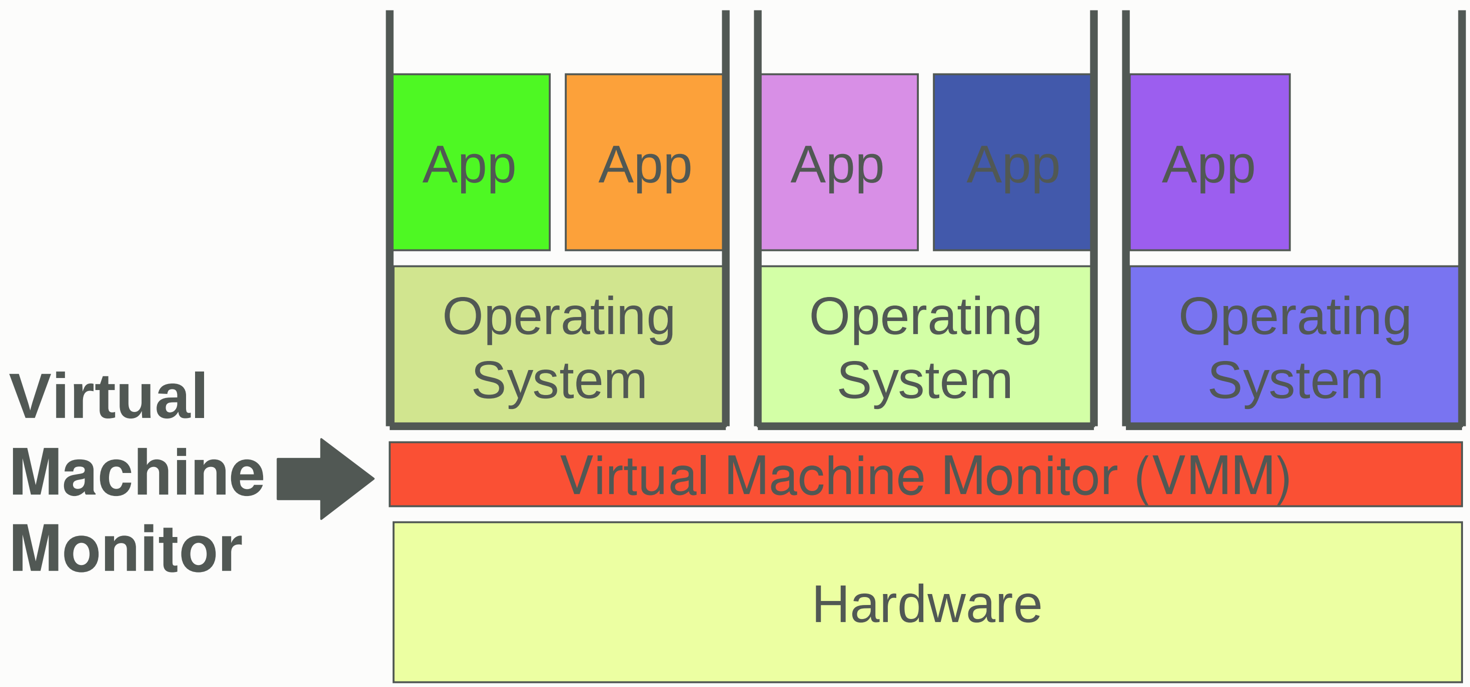
  Solution using virtual machine monitors

Talk Outline

- What is a virtual machine monitor(VMM)?
  - IBM mainframes
  - VMware Inc. – Commodity x86 computers
- How do they work?
  - A quick look under the hood.
- VMM characteristics, attributes, and capabilities
  - Compatibility, performance, isolation, encapsulation
- Some applications of VMMs to increase reliability
- Detailed examples
- Conclusion

Virtual Machine Monitor

- Thin software layer that virtualizes the hardware
  - Exports abstraction of virtual machines



Old idea from the 1960s

- IBM VM/370 – A VMM for IBM mainframe
  - Multiplex multiple OS environments on expensive hardware.
  - Desirable when few machine around.
- Popular research idea in 1960s and 1970s
  - Entire conferences on virtual machine monitor
- Interest died out in the 1980s and 1990s.
  - Hardware got cheap.
- Why did we think this was interesting again?
  - Difference problems today – complex software
  - VMM attributes still relevant

Virtual Machine Monitor Implementation

- Need to virtualize all the hardware of the machine
  - CPU, Memory, I/O
- Need to use hardware to directly support virtual machines
  - Virtual CPU execution directly uses real CPU
  - Memory of virtual machine uses real memory
  - I/O devices supported using real I/O devices
- Definition: virtualizability
  - Hardware is virtualizable if a virtual machine monitor can control it enough to directly support a virtual machine.
- Use to be a standard part of architecture curriculum
  - Not even mentioned in standard textbooks
  - Most architectures today are not strictly virtualizable (x86, RISC)

CPU virtualization

- Monitor needs to **safely** give CPU to virtual machine
  - Virtual machine should be able to damage monitor or other VMs
  - Monitor should be able to get control and switch running VM
    - *Monitor needs to multiplex virtual CPUs on real CPUs*
      - Like an OS context switch: Save one state/Restore another
- Basic trick: Run monitor in most privileged mode
  - VMs always run in less privileged modes.
    - *For speed, use direct execution to run VMs*
    - *For protection, use protection mechanisms of CPU*
  - Monitor needs to hide and fake-out software to run correctly.
    - *VMs traps into the monitor to do any privileged operations.*
- Done right, software can’t tell virtual CPUs from real CPU

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.

Physical memory virtualization

- Need to implement a *virtual* physical memory
  - Logically need additional level of indirection
    - *VM's VA -> VM's PA -> machine address*
  - Can be folded into page tables: VA->machine address
- Trick: Monitor keeps shadow of VM's page table
  - Contains mapping to physical memory allocated for that VM
  - Monitor can demand page the virtual machine
- Again, uses hardware protection
  - Monitor never maps itself into VM's page table
  - Monitor never maps memory allocated to other VMs in VM's page table
- Need a place to load monitor in memory

I/O device virtualization

- Need to either emulate or map through I/O device
  - Example map through: virtual disk == physical disk
  - Example emulate: virtual disk == blocks on physical disk
- Monitor needs to interpose on all I/O device request
  - Intercept or redirect all program input/output
  - Relocate all DMA requests
- Hard to do for an arbitrary I/O device
  - How do you know what's an DMA address?
- Multiplex devices: Keyboard, mouse, video, ..

Virtual machine monitor attributes

- Software compatibility
  - Runs pretty much all software
- Low overheads/High performance
  - Near “raw” machine performance
- Complete isolation
  - Total data isolation between virtual machines
- Encapsulation
  - Virtual machines are not tied to physical machines

Software compatibility

- Key: Make virtual machine abstraction match real HW
  - All software that runs on real HW runs in VM
  - Compare to abstract virtual machines such as Java
- Example: VMware runs

  DOS, Win 3.1,95,98,NT,2000,ME,XP; Linux, OS/2, Freebsd, etc.
- Easiest way to maintain backward compatibility
  - Avoid death to due cost of backward compatibility
- What doesn't run in VMM:
  - Super timing sensitive:
    - *e.g. syscall trap should take exactly 60 cycles*
  - Hardware I/O device dependences:
    - *Code assumes it can talk to latest nvidia graphics processors*
- **Everything** else runs regardless of SW complexity!

Low overhead/High Performance

- Key: Configure HW to directly run Virtual Machines
  - Use CPU to emulate a virtual CPU
  - Use real physical memory to emulate virtual physical memory
  - Emulate a disk with a disk, etc.
- Trick from 1960s:
  - Configure hardware to safely give it to virtual machine
  - VMM gets control on any privileged operation
- Virtual machine runs within a few percent of native

Isolation capability

- Key: Use HW protection mechanisms to isolate VMs
  - Example: Protection rings, MMU protection bits
  - Unbreakable security
- Complete isolation
  - Code running in a VM can’t read,modify, break,etc:

    Other virtual machines

    The virtual machine monitor
- Isolation comparable to separate physical machines
  - Handle accidents (e.g. software bugs)
  - Malicious attacks (e.g. hackers)

Encapsulation

- Key: VMM sits between VM and hardware
  - Virtual machine is not tied to physical hardware
- VMM can completely isolate VM from hardware:
  - Support for checkpoint/restore operations
  - Virtual machine migration
  - Undo execution
- Hardware independence
  - VMM maps “standard” virtual HW to real HW
    - *VMM provides the “conversion” layer*

VMMs capabilities

- An application of an level of indirection
  - Between software and hardware
  - Transparently interpose on all communication:
    - *CPU, memory, I/O devices (disk, net, etc.)*
- Standard argument:
  - \- Additional overheads
  - \+ Glorious benefits
- Simple examples:
  - Resource management
  - OS enhancement

Resource management

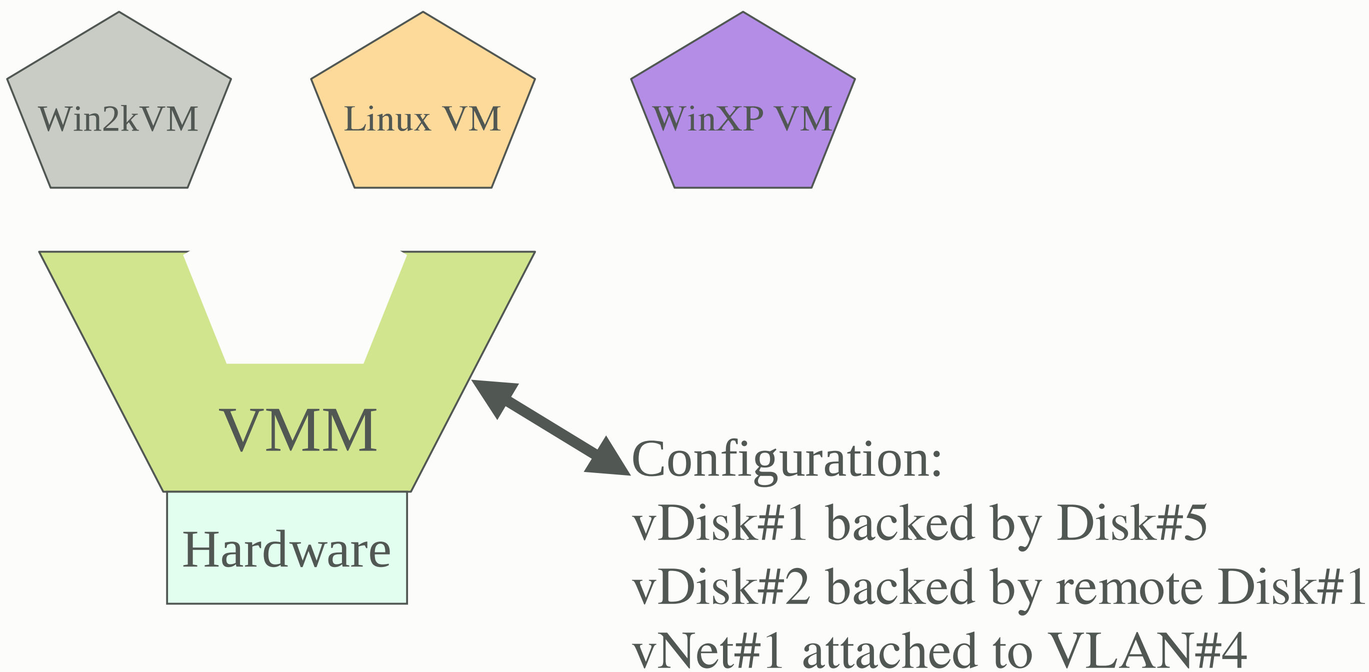
- Key: VMM controls all HW: CPU, Memory, I/O devices
  - VMM can decide how much of each each VM gets
- Can overcommit resources
  - More virtual CPUs than physical CPUs
  - More virtual physical memory than physical memory
- VMM can do performance isolation
  - Make guarantees to the VMs
  - Limit the resources used by a VM

OS enhancements

- Key: VMM layer can enhance the OS running in the VM
  - Some functionality easier to do in VMM than OS
- Example: Stanford Disco VMM
  - Run OSes on scalable multiprocessors
- Examples from VMware product:
  - Check & fast restore capabilities
  - Undoable disks
- Many more
  - *Internet Edge deployment*
  - *Application Service Provider environment*
  - *Software fault tolerance*
- Sometimes faster and easiest way of improvement.

Virtual Machines Vision

- All software runs in a virtual machine.
- All hardware runs a virtual machine monitor.



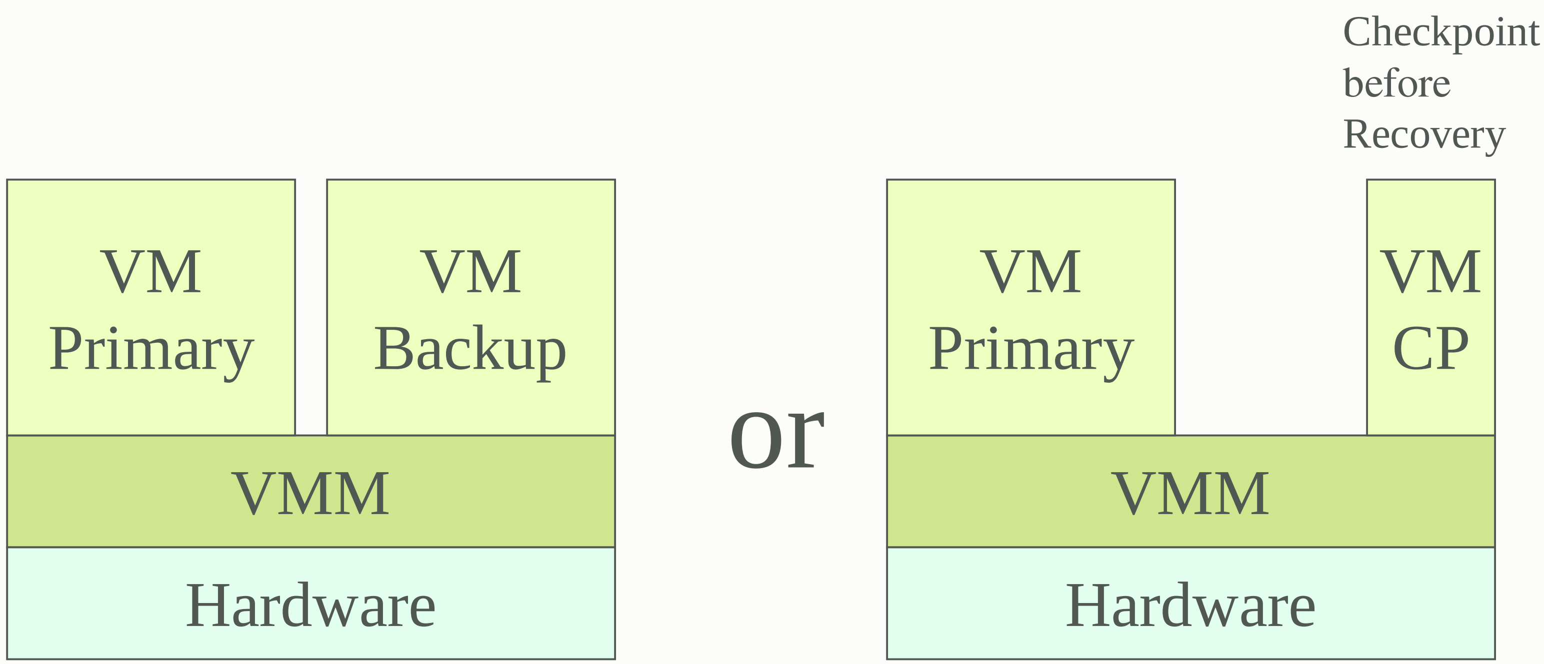
The Matrix analogy

Examples of using VMs for reliability

- Lower cost replication
  - Replicate virtual machines not physical machines
- Faster recovery
  - Use restore to skip boot, etc.
- Partitioning for reliability
  - Fault containment, reduce concurrency demands on OS

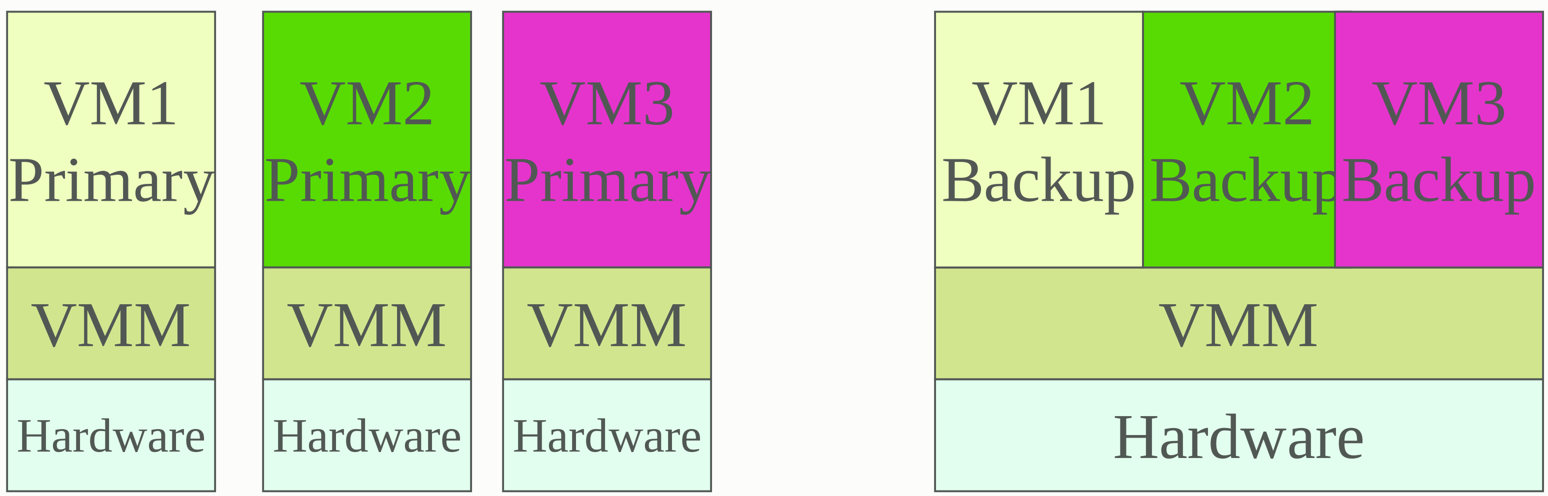
Low cost replication example#1

- Assumption: Hardware doesn't fail, but software does
  - Replicate software not hardware



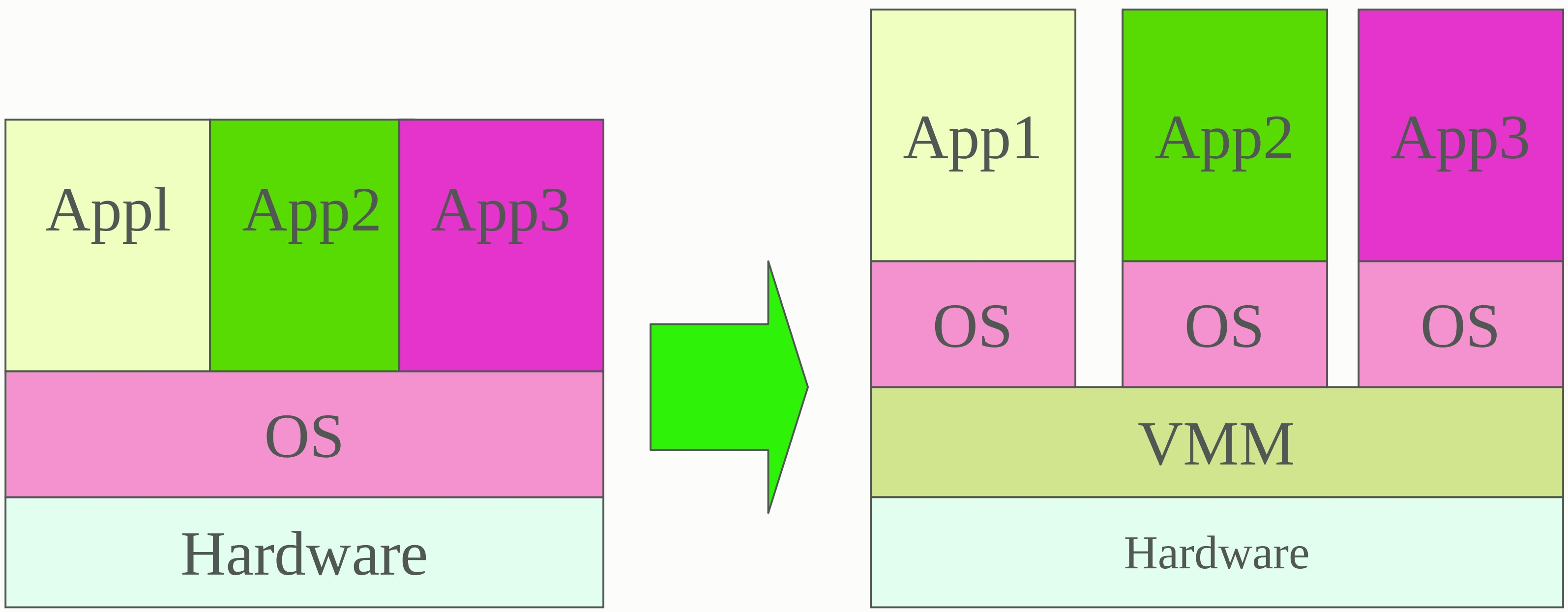
Low cost replication #2

- Assumption: Unlikely that more than one fail at a time



Partitioning for reliability

- Assumption: An OS doing one thing is more stable than OS doing more than one thing.



Detailed Examples

- Moving content to the network edge
- Computing utility