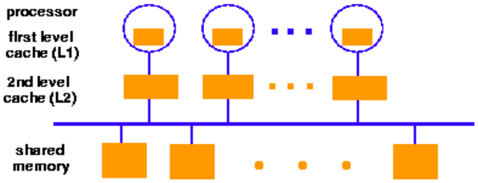
Multiprocessor Scheduling

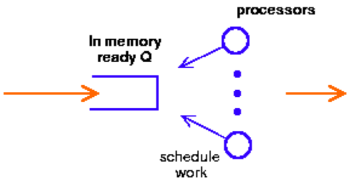
- Will consider only shared memory multiprocessor or multi-core CPU



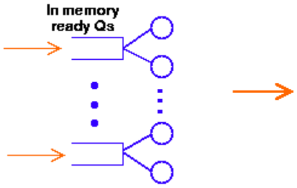
- Salient features:
  - One or more caches: cache affinity is important
  - Semaphores/locks typically implemented as spin-locks: preemption during critical sections
- Multi-core systems: some caches shared (L2,L3); others are not

Multiprocessor Scheduling

- Central queue – queue can be a bottleneck



- Distributed queue – load balancing between queue



Multiprocessor Scheduling

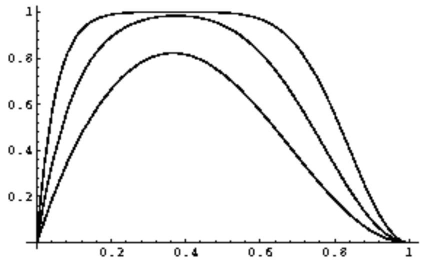
- Common mechanisms combine central queue with per processor queue (SGI IRIX)
- Exploit *cache affinity* – try to schedule on the same processor that a process/thread executed last
- Context switch overhead
  - Quantum sizes larger on multiprocessors than uniprocessors

Parallel Applications on SMPs

- Effect of spin-locks: what happens if preemption occurs in the middle of a critical section?
  - Preempt entire application (co-scheduling)
  - Raise priority so preemption does not occur (smart scheduling)
  - Both of the above
- Provide applications with more control over its scheduling
  - Users should not have to check if it is safe to make certain system calls
  - If one thread blocks, others must be able to run

Distributed Scheduling: Motivation

- Distributed system with *N* workstations
  - Model each w/s as identical, independent M/M/1 systems
  - Utilization *u*, P(system idle)=1-*u*
- What is the probability that at least one system is idle and one job is waiting?



Implications

- Probability high for moderate system utilization
  - Potential for performance improvement via load distribution
- High utilization => little benefit
- Low utilization => rarely job waiting
- Distributed scheduling (aka load balancing) potentially useful
- What is the performance metric?
  - Mean response time
- What is the measure of load?
  - Must be easy to measure
  - Must reflect performance improvement

Design Issues

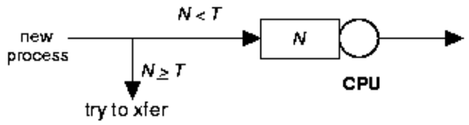
- Measure of load
  - Queue lengths at CPU, CPU utilization
- Types of policies
  - Static: decisions hardwired into system
  - Dynamic: uses load information
  - Adaptive: policy varies according to load
- Preemptive versus non-preemptive
- Centralized versus decentralized
- Stability: $\lambda>\mu$ => instability, $\lambda_1+\lambda_2<\mu_1+\mu_2$=>load balance
  - Job floats around and load oscillates

Components

- *Transfer policy:* **when** to transfer a process?
  - Threshold-based policies are common and easy
- *Selection policy:* **which** process to transfer?
  - Prefer new processes
  - Transfer cost should be small compared to execution cost
    - Select processes with long execution times
- *Location policy:* **where** to transfer the process?
  - Polling, random, nearest neighbor
- *Information policy*: when and from where?
  - Demand driven [only if sender/receiver], time-driven [periodic], state-change-driven [send update if load changes]

Sender-initiated Policy

- *Transfer policy*



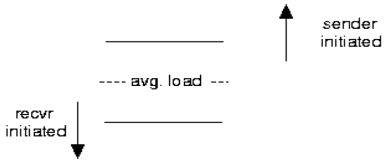
- *Selection policy*: newly arrived process
- *Location policy*: three variations
  - *Random*: may generate lots of transfers => limit max transfers
  - *Threshold:* probe *n* nodes sequentially
    - Transfer to first node below threshold, if none, keep job
  - *Shortest*: poll N_p nodes in parallel
    - Choose least loaded node below *T*

Receiver-initiated Policy

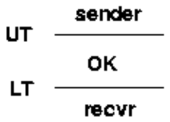
- Transfer policy: If departing process causes load < *T*, find a process from elsewhere
- Selection policy: newly arrived or partially executed process
- Location policy:
  - Threshold: probe up to N_p other nodes sequentially
    - Transfer from first one above threshold, if none, do nothing
  - Shortest: poll *n* nodes in parallel, choose node with heaviest load above *T*

Symmetric Policies

- Nodes act as both senders and receivers: combine previous two policies without change
  - Use average load as threshold



- Improved symmetric policy: exploit polling information
  - Two thresholds: *LT, UT, LT* <= *UT*
  - Maintain sender, receiver and OK nodes using polling info
  - Sender: poll first node on receiver list …
  - Receiver: poll first node on sender list …



Case Study 1 : V-System (Stanford)

- State-change driven information policy
  - Significant change in CPU/memory utilization is broadcast to all other nodes
- *M* least loaded nodes are receivers, others are senders
- Sender-initiated with new job selection policy
- Location policy: probe random receiver, if still receiver, transfer job, else try another

Case study 2: Sprite (Berkeley)

- Workstation environment => owner is king!
- Centralized information policy: coordinator keeps info
  - State-change driven information policy
  - Receiver: workstation with no keyboard/mouse activity for 30 seconds *and* # active processes < number of processors
- Selection policy: manually done by user => workstation becomes sender
- Location policy: sender queries coordinator
- WS with foreign process becomes sender if user becomes active: selection policy=> home workstation

Sprite (contd)

- Sprite process migration
  - Facilitated by the Sprite file system
  - State transfer
    - Swap everything out
    - Send page tables and file descriptors to receiver
    - Demand page process in
    - Only dependencies are communication-related
      - Redirect communication from home WS to receiver

Case Study 3 : Volunteer Computing

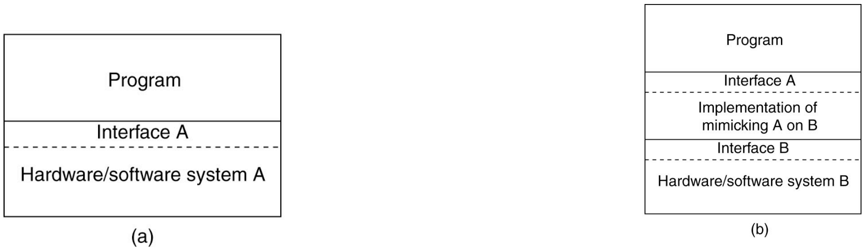
- Internet scale operating system (ISOS)
  - Harness compute cycles of thousands of PCs on the Internet
  - PCs owned by different individuals
  - Donate CPU cycles/storage when not in use (pool resouces)
  - Contact coordinator for work
  - Coordinator: partition large parallel app into small tasks
  - Assign compute/storage tasks to PCs
- Examples: Seti@home, BOINC, P2P backups
  - Volunteer computing

Case study 4 : Condor

- Condor: use idle cycles on workstations in a LAN
- Used to run large batch jobs, long simulations
- Idle machines contact condor for work
- Condor assigns a waiting job
- User returns to workstation => suspend job, migrate
  - supports process migration
- Flexible job scheduling policies

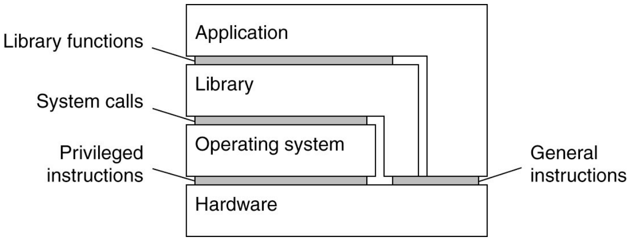
- Sun Grid Engine: similar features as Condor

Virtualization


Program
Interface A
Hardware/software system A
(a)
Program
Interface A
Implementation of mimicking A on B
Interface B
Hardware/software system B
(b)

- Virtualization: extend or replace an existing interface to mimic the behavior of another system.
  - Introduced in 1970s: run legacy software on newer mainframe hardware
- Handle platform diversity by running apps in VMs
  - Portability and flexibility

Types of Interfaces



- Different types of interfaces
  - Assembly instructions
  - System calls
  - APIs
- Depending on what is replaced /mimiced, we obtain different forms of virtualization

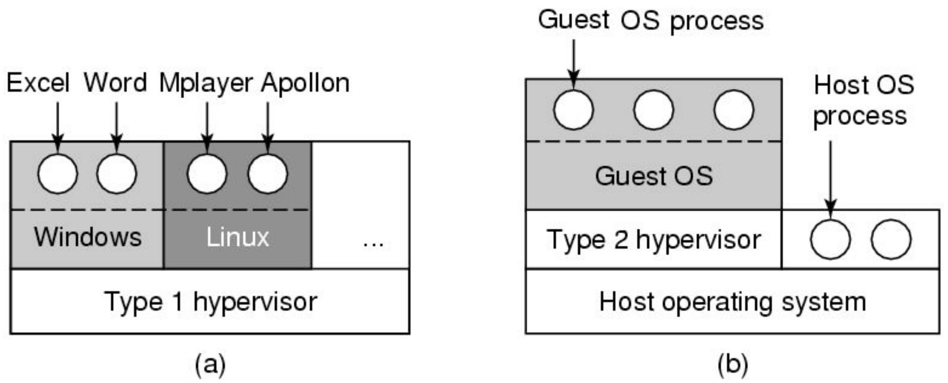
Types of Virtualization

- Emulation
  - VM emulates/simulates complete hardware
  - Unmodified guest OS for a different PC can be run
    - Bochs, VirtualPC for Mac, QEMU
- Full/native Virtualization
  - VM simulates "enough" hardware to allow an unmodified guest OS to be run in isolation
    - Same hardware CPU
  - IBM VM family, VMWare Workstation, Parallels,…

Types of virtualization

- Para-virtualization
  - VM does not simulate hardware
  - Use special API that a modified guest OS must use
  - Hypercalls trapped by the Hypervisor and serviced
  - Xen, VMWare ESX Server
- OS-level virtualization
  - OS allows multiple secure virtual servers to be run
  - Guest OS is the same as the host OS, but appears isolated
    - apps see an isolated OS
  - Solaris Containers, BSD Jails, Linux Vserver
- Application level virtualization
  - Application is gives its own copy of components that are not shared
    - (E.g., own registry files, global objects) - VE prevents conflicts
  - JVM, Rosetta on Mac (also emulation), WINE

Types of Hypervisors

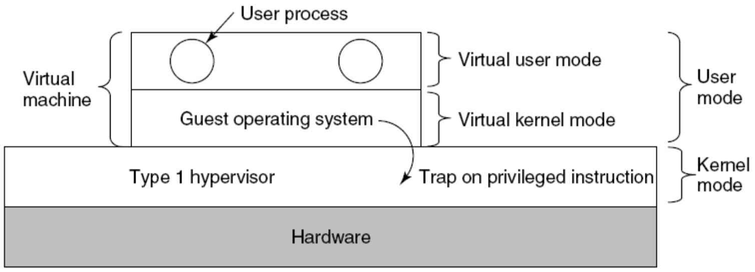


- Type 1: hypervisor runs on “bare metal”
- Type 2: hypervisor runs on a host OS
  - Guest OS runs inside hypervisor
- Both VM types act like real hardware

How Virtualization works?

- CPU supports kernel and user mode (ring0, ring3)
  - Set of instructions that can only be executed in kernel mode
    - I/O, change MMU settings etc -- *sensitive instructions*
  - Privileged instructions: cause a trap when executed in kernel mode
- Result: type 1 virtualization feasible if sensitive instruction subset of privileged instructions
- Intel 386: ignores sensitive instructions in user mode
  - Can not support type 1 virtualization
- Recent Intel/AMD CPUs have hardware support
  - Intel VT, AMD SVM
    - Create containers where a VM and guest can run
    - Hypervisor uses hardware bitmap to specify which inst should trap
    - Sensitive inst in guest traps to hypervisor

Type 1 hypervisor

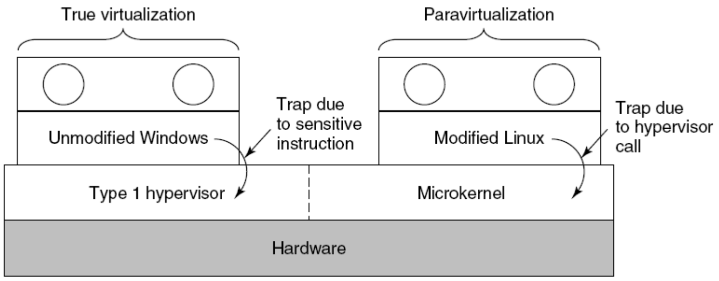


- Unmodified OS is running in user mode (or ring 1)
  - But it thinks it is running in kernel mode (*virtual kernel mode)*
  - privileged instructions trap; sensitive inst-> use VT to trap
  - Hypervisor is the “real kernel”
    - Upon trap, executes privileged operations
    - Or emulates what the hardware would do

Type 2 Hypervisor

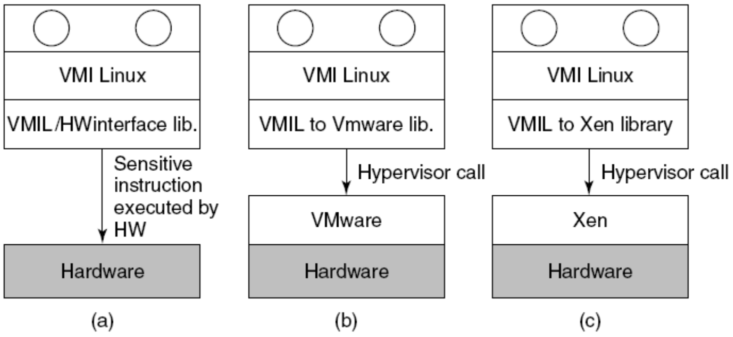
- VMWare example
  - Upon loading program: scans code for basic blocks
  - If sensitive instructions, replace by Vmware procedure
    - Binary translation
  - Cache modified basic block in VMWare cache
    - Execute; load next basic block etc.
- Type 2 hypervisors work without VT support
  - Sensitive instructions replaced by procedures that emulate them.

Paravirtualization



- Both type 1 and 2 hypervisors work on unmodified OS
- Paravirtualization: modify OS kernel to replace all sensitive instructions with hypercalls
  - OS behaves like a user program making system calls
  - Hypervisor executes the privileged operation invoked by hypercall.

Virtual machine Interface



- Standardize the VM interface so kernel can run on bare hardware or any hypervisor

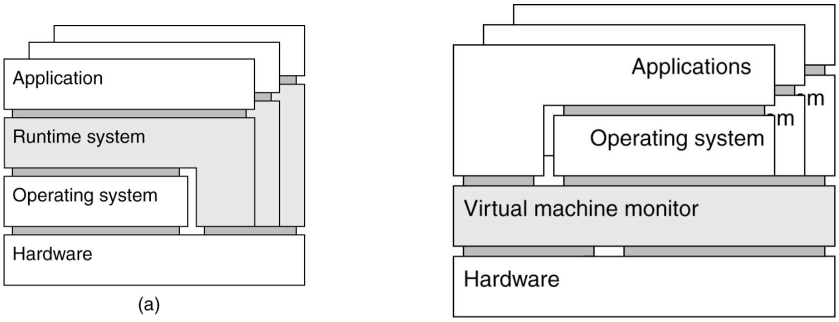
Memory virtualization

- OS manages page tables
  - Create new pagetable is sensitive -> traps to hypervisor
- hypervisor manages multiple OS
  - Need a second shadow page table
  - OS: VM virtual pages to VM's physical pages
  - Hypervisor maps to actual page in shadow page table
  - Two level mapping
  - Need to catch changes to page table (not privileged)
    - Change PT to read-only - page fault
    - Paravirtualized - use hypercalls to inform

I/O Virtualization

- Each guest OS thinks it "owns" the disk
- Hypervisor creates "virtual disks"
  - Large empty files on the physical disk that appear as "disks" to the guest OS
    - Hypervisor converts block # to file offset for I/O
  - DMA need physical addresses
    - Hypervisor needs to translate

Examples



(a)

(b)

- Application-level virtualization: “process virtual machine”
- VMM /hypervisor

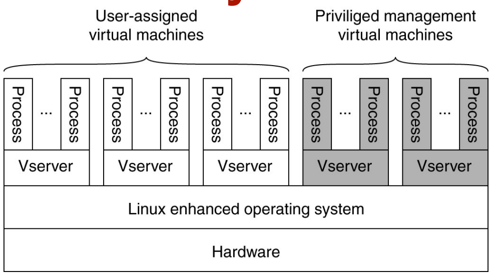
Virtual Appliances & Multi-Core

- Virtual appliance: pre-configured VM with OS/ apps pre-installed
  - Just download and run (no need to install/comfigure)
  - Software distribution using appliances
- Multi-core CPUs
  - Run multiple VMs on multi-core systems
  - Each VM assigned one or more vCPU
  - Mapping from vCPUs to physical CPUs

Use of Virtualization Today

- Data centers:
  - server consolidation: pack multiple virtual servers onto a smaller number of physical server
    - saves hardware costs, power and cooling costs
- Cloud computing: rent virtual servers
  - cloud provider controls physical machines and mapping of virtual servers to physical hosts
  - User gets root access on virtual server
- Desktop computing:
  - Multi-platform software development
  - Testing machines
  - Run apps from another platform

Case Study: PlanetLab



User-assigned virtual machines

Priviliged management virtual machines

Process ... Process | Process ... Process | Process ... Process | Process ... Process | Process ... Process

Vserver | Vserver | Vserver | Vserver | Vserver

Linux enhanced operating system

Hardware

- Distributed cluster across universities
  - Used for experimental research by students and faculty in networking and distributed systems
- Uses a virtualized architecture
  - Linux Vservers
  - Node manager per machine
  - Obtain a “slice” for an experiment: slice creation service