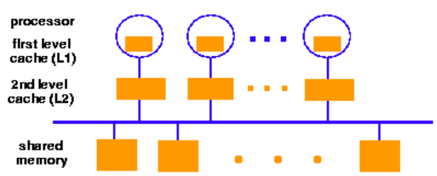
Distributed and Cluster Scheduling

- Part 1: Multiprocessor scheduling
- Part 2: Distributed Scheduling
- Part 3: Cluster Scheduling

Part 1: Multiprocessor Scheduling

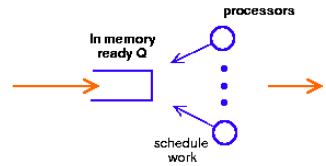
- Shared memory symmetric multiprocessor (SMP) or multi-core CPU



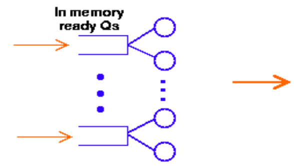
- Salient features: One or more caches: cache affinity is important
  – Semaphores/locks typically implemented as spin-locks: preemption during critical sections
- Multi-core systems: some caches shared (L2,L3); others are not

Multiprocessor Scheduling

- **Central** queue
  - queue can be a bottleneck;
  - utilizes all processors;
  - poor cache affinity



- **Distributed** queue
  - imbalance between queues
  - load balancing between queue
  - good cache affinity



- Exploit *cache affinity* – try to schedule on the same processor that a process/thread executed last

Gang Scheduling

- *Gang scheduling*: schedule **parallel application** at once on all cores/processors
  - Reduces waiting/blocking from message passing/IPC
  - Same idea also applies to a cluster setting

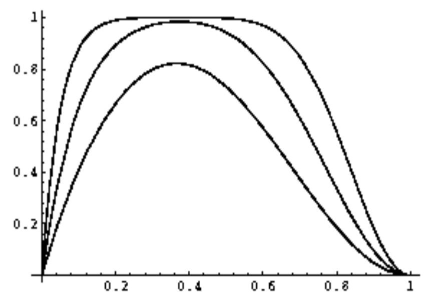
- Effect of spin-locks: what happens if preemption occurs in the middle of a critical section?
  - Preempt entire application (co-scheduling)
  - Raise priority so preemption does not occur (smart scheduling)
  - Both of the above

Part 2: Distributed Scheduling

- Distributed scheduling arose in the workstation era
- Workstation on every desk, many idle
  - **Harness idle cycles on workstations**
  - Scheduling in a *Network of Workstations (NoW)*
    - User submits job to local machine
    - OS schedules locally if load is low
    - OS schedules remotely on an idle machine otherwise
- Distributed system with N workstations
  - To understand benefits of the approach:
  - Model each w/s as identical, independent M/M/1 systems
  - Utilization u, P(system idle)=1-u

Harnessing Idle Cycles in NoW

- What is the probability that at least one system is idle and one job is waiting?
- **High** utilization => little benefit
- **Low** utilization => rarely job waiting
- Probability high for moderate system utilization
  - Potential for performance improvement
  - Distributed scheduling (aka load balancing) useful
- What is the performance metric?
  - Mean response time
- What is the measure of load?
  - Must be easy to measure and reflect performance improvement
  - Queue lengths at CPU, CPU utilization
- Stability: $\lambda > \mu$ => instability, $\lambda_1+\lambda_2<\mu_1+\mu_2$=>load balance
  - Job floats around and load oscillates

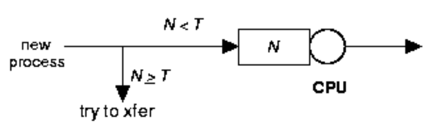


Components

- *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*

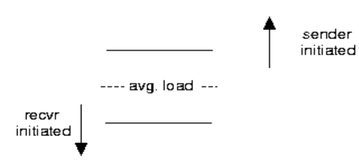
Receiver-initiated Policy

- 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

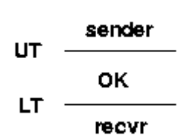


- Improved symmetric policy: exploit polling information
  – Two thresholds: *LT, UT, LT <= UT*

  – 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 from *M*, 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 is a building block for scheduling on to remote machines
  - 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: Condor

- Condor: use idle cycles on workstations in a LAN
- Active project at U. Wisconsin, can use even today
- 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

Case Study 4: Volunteer Computing

- Modern way to harness idle cycles in PCs over WAN
  - Harness compute cycles of thousands of PCs on the Internet
- Volunteer Computing
  - PCs owned by different individuals
  - Donate CPU cycles/storage when not in use (pool resouces)
  - Idling machine contacts 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

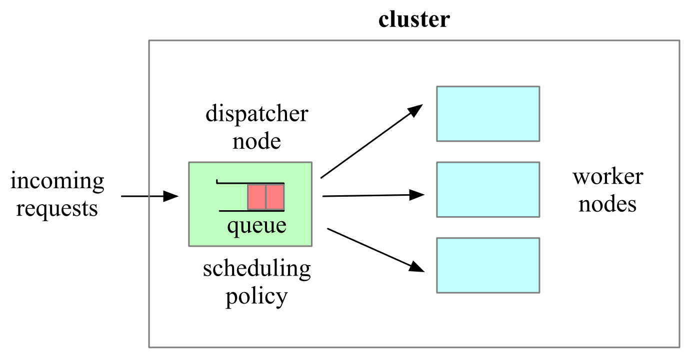
Part 3: Cluster Scheduling

- Scheduling tasks on to a cluster of servers
  - Machines are cheap, no need to rely on idle PCs anymore
  - Use a cluster of powerful servers to run tasks
  - User requests sent to the cluster (rather than a idle PC)

- **Interactive** applications
  - Web servers use a cluster of servers
  - "Job" is a single HTTP request; optimize for response time
- **Batch** applications
  - Job is a long running computation; optimize for throughput

Typical Cluster Scheduler

- Dispatcher node assigns queued requests to worker nodes as per a scheduling policy



Scheduling in Clustered Web Servers

- Distributed scheduling in large web servers
  - N nodes, one node acts as load balancer/dispatcher
  - other nodes are replica worker nodes ("server pool")
- Requests arrive into queue at load balancer node
  - Dispatcher schedules request onto an worker node
- How to decide which node to choose?
  - Scheduling policies: least loaded, round robin
    - Weighted round robin when servers are heterogeneous
- Session-level versus request-level load balancing
  - Web server maintain session state for client (e.g., shopping cart)
  - Perform load balancing at session granularity
    - All requests from client session sent to same worker

Scheduling Batch Jobs

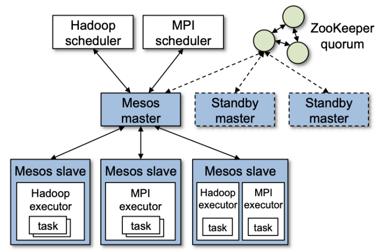
- Batch jobs are non-interactive tasks
  - ML training, data processing tasks, simulations
- Batch scheduling in a server cluster
  - Users submit job to a queue, dispatcher schedules jobs
- SLURM: Simple Linux Utility for Resource Management
  - Linux batch scheduler; runs on > 50% supercomputers
  - Nodes partitioned into groups; each group has job queue
    - Specify size, time limits, user groups for each queue
    - Example: short queue, long queue
    - Many policies: FCFS, priority, gang scheduling
    - Exclusive or shared access to nodes (e.g., MPI jobs)
- Others: SunGridEngine, DQS, Load Leveler, IBM LSF

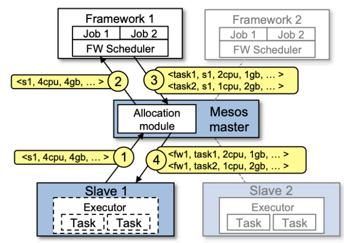
Mesos Scheduler

- Mesos: Cluster manager and scheduler for multiple frameworks
  - Cluster typically runs multiple frameworks: batch, Spark, …
    - Statically partition cluster, each managed by a scheduler
  - Mesos: fine-grain server sharing between frameworks
- Two-level approach: allocate resources to frameworks, framework allocates resources to tasks
- **Resource Offers**: bundle of resources offered to framework
  - Framework can accept or reject offer
  - Higher-level policy (e.g., fair share) governs allocation; resource offers used to offer resources
  - Framework-specific scheduling policy allocates to tasks
  - Framework can not ask for resources; only accept/reject resource offers (Paper shows this is sufficient).

Mesos Scheduler

- Four components: **coordinator**, Mesos **worker**, framework **scheduler**, **executor** on server nodes
- Step 1: worker node (6 core, 6GB) becomes idle, reports to coordinator
- Step 2: Coordinator invokes policy, decides to allocate to Framework 1. Sends resource offer
- Step 3: Framework accepts, scheduler assigns task 1 (2C, 2GB) and task 2 (2C, 3GB)
- Step 4: Coordinator sends tasks to executor on node
- Unused resources (2C, 1GB): new offer



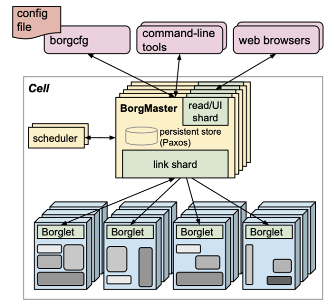


Borg Scheduler

- Google's cluster scheduler: scheduling at very large scales
  - run hundreds of thousands of concurrent jobs onto tens of thousands of server
  - Borg's ideas later influenced *kubernates*
- Design Goals:
  - hide details of resource management and failures from apps
  - Operate with high reliability (manages gmail, web search, ..)
  - Scale to very large clusters
- Designed to run two classes: interactive and batch
  - Long running interactive jobs (prod job) given priority
  - Batch jobs (non-prod jobs) given lower priority
  - % of interactive and batch jobs will vary over time

Borg Scheduler

- Cell: group of machines in a cluster (~10K servers)
- Borg: matches jobs to cells
  - jobs specify resource needs
  - Borg finds a cell/machine to run a job
  - job needs can change (e.g., ask for more)
- Use resource reservations (“alloc”)
  - alloc set: reservations across machines
  - Schedule job onto alloc set
- Preemption: higher priority job can preempt a lower priority job if there are insufficient resources
- Borg Master coördinator: replicated 5 times, uses paxos
- Priority queue to schedule jobs: uses best-fit, worst-fit

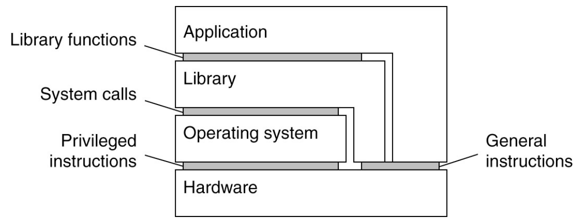


Virtualization

(a) (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

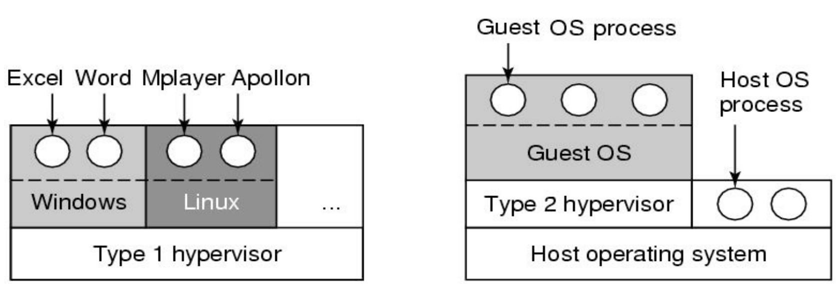
Types of Virtualization

- 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, VirtualBox

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, Linux containers, Docker
- 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



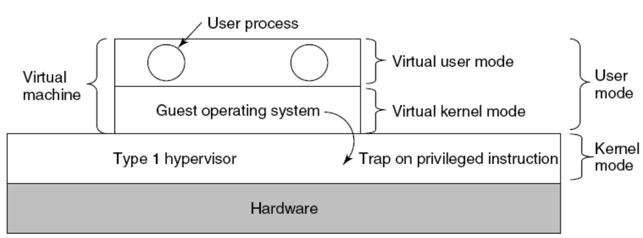
(a) (b)

- 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

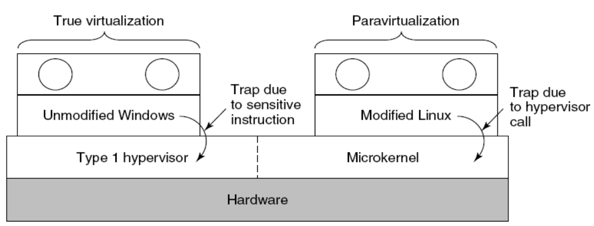


- Unmodified OS is running in user mode (or ring 1)
  - But it thinks it is running in kernel mode (*virtual kernel mode)*
  - privileged instructions trap; sensitive inst-> use VT to trap
  - Hypervisor is the “real kernel”
    - Upon trap, executes privileged operations
    - Or emulates what the hardware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

Type 2 Hypervisor

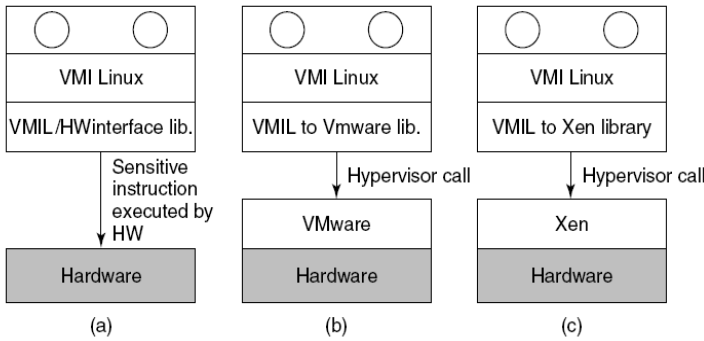
- VMWare example
  - Upon loading program: scans code for basic blocks
  - If sensitive instructions, replace by Vmware procedure
    - Binary translation
  - Cache modified basic block in VMWare cache
    - Execute; load next basic block etc.
- Type 2 hypervisors work without VT support
  - Sensitive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

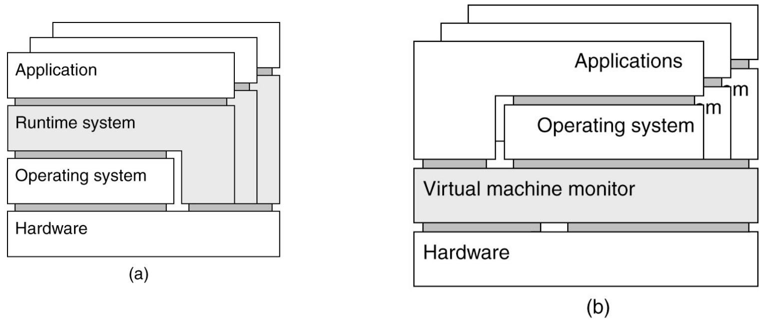
Memory virtualization

- 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



- Application-level virtualization: "process virtual machine"
- VMM /hypervisor

Virtual Appliances & Multi-Core

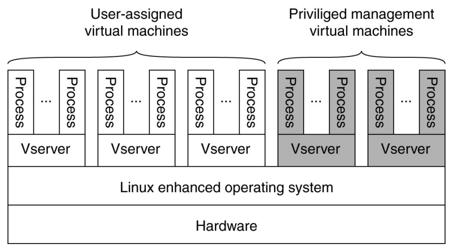
- Virtual appliance: pre-configured VM with OS/ apps pre-installed
  - Just download and run (no need to install/configure)
  - Software distribution using appliances
- Multi-core CPUs
  - Run multiple VMs on multi-core systems
  - Each VM assigned one or more vCPU
  - Mapping from vCPUs to physical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

- Today: Virtual appliances have evolved into docker containers

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



- 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