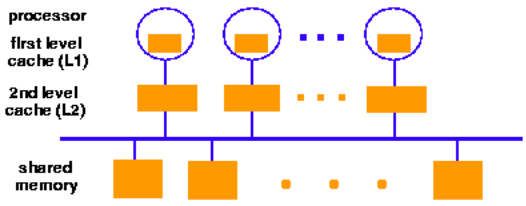
Distributed and Cluster Scheduling

- 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

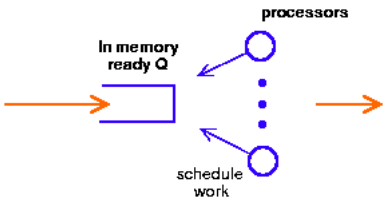


•Salient features: One or more caches: cache affinity is important
  – Semaphores/locks typically implemented as spin-locks: preemption during critical sections

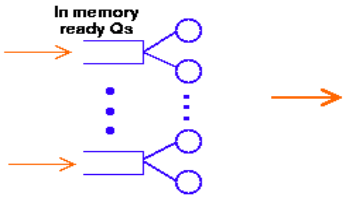
•Multi-core systems: some caches shared (L2,L3); others are not

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

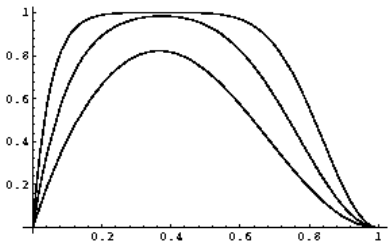
- *Gang scheduling*: schedule **parallel application** at once on all cores/processors
  - Reduces waiting/blocking from message passing/IPC
  - Same idea also applies to a cluster setting
- Effect of spin-locks: what happens if preemption occurs in the middle of a critical section?
  - Preempt entire application (co-scheduling)
  - Raise priority so preemption does not occur (smart scheduling)
  - Both of the above

Part 2: Distributed Scheduling

- Distributed scheduling arouse 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



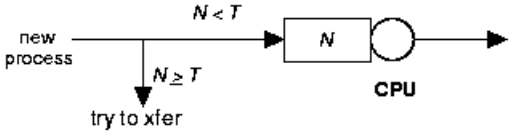
- What is the measure of load?
  - Must be easy to measure and reflect performance improvement
  - Queue lengths at CPU, CPU utilization
- Stability: $\lambda>\mu$ => instability, $\lambda_1+\lambda_2<\mu_1+\mu_2$=>load balance
  - Job floats around and load oscillates

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*



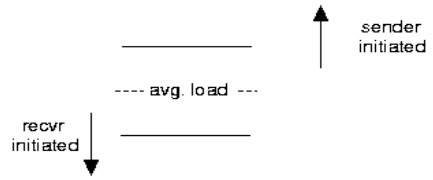
- *Selection policy*: newly arrived process
- *Location policy*: three variations
  - *Random*: may generate lots of transfers => limit max transfers
  - *Threshold:* probe *n* nodes sequentially
    - Transfer to first node below threshold, if none, keep job
  - *Shortest*: poll N_p nodes in parallel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

Receiver-initiated Policy

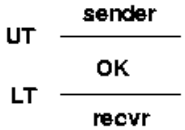
- Transfer policy: If departing process causes load < *T*, find a process from elsewhere
- Selection policy: newly arrived or partially executed process
- Location policy:
  - Threshold: probe up to N_p other nodes sequentially
    - Transfer from first one above threshold, if none, do nothing
  - Shortest: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

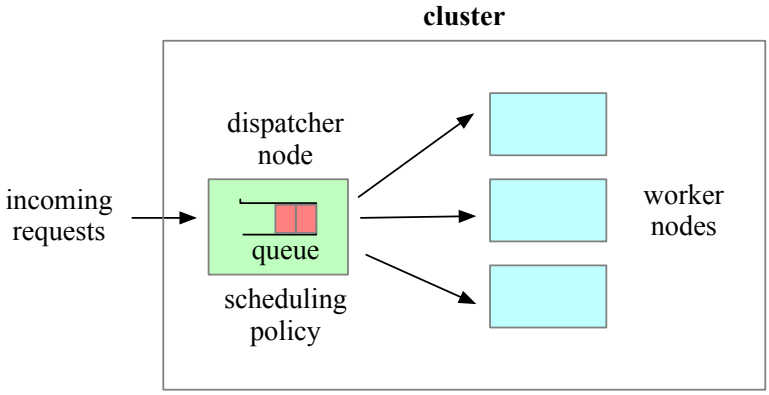
Part 3: Cluster Scheduling

- 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

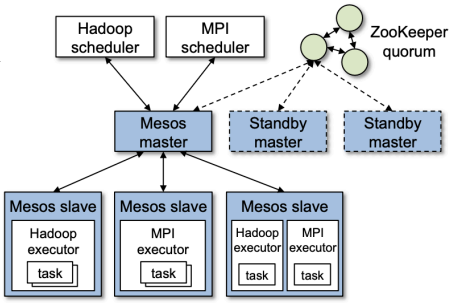
- Batch jobs are non-interactive tasks
  - ML training, data processing tasks, simulations
- Batch scheduling in a server cluster
  - Users submit job to a queue, dispatcher schedules jobs
- SLURM: Simple Linux Utility for Resource Management
  - Linux batch scheduler; runs on > 50% supercomputers
  - 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

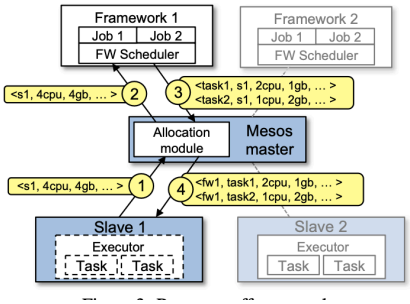
Mesos Scheduler

- 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



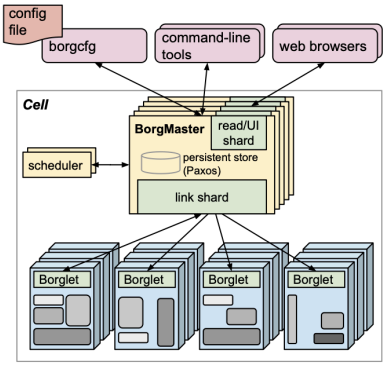


Borg Scheduler

- 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 to
- Priority queue to schedule jobs: uses best-fit, worst-fit