Administrivia

- Assignment 1 due end of next week
- Please, please, please turn in your own work
  - Most of you would never think of cheating, and I apologize that I even have to bring this up
  - 50% of honor-code violations are in CS
  - If you are in trouble, ask for extensions, ask for help
  - But if you copy code, we have to turn it over to Judicial Affairs
  - If you copy code, re-format, re-name variables, etc., you will still be caught. See MOSS for some of theory behind this.

CPU Scheduling

- The scheduling problem:
  - Have $K$ jobs ready to run
  - Have $N \geq 1$ CPUs
  - Which jobs to assign to which CPU(s)
- When do we make decision?

Scheduling criteria

- Why do we care?
  - What goals should we have for a scheduling algorithm?

- Throughput – # of pros that complete per unit time
  - Higher is better

- Turnaround time – time for each proc to complete
  - Lower is better

- Response time – time from request to first response (e.g., key press to character echo, not launch to exit)
  - Lower is better

- Above criteria are affected by secondary criteria
  - CPU utilization – keep the CPU as busy as possible
  - Waiting time – time each proc waits in ready queue

Example: FCFS Scheduling

- Run jobs in order that they arrive
  - Called “First-come first-served” (FCFS)
  - E.g., Say $P_1$ needs 24 sec, while $P_2$ and $P_3$ need 3.
  - Say $P_2$, $P_3$ arrived immediately after $P_1$, get:

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>$P_1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>$P_2$</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>$P_3$</td>
<td></td>
</tr>
</tbody>
</table>

- Dirt simple to implement—how good is it?
- Throughput: 3 jobs / 30 sec = 0.1 jobs/sec
- Turnaround Time: $P_1 : 24$, $P_2 : 27$, $P_3 : 30$
  - Average TT: $(24 + 27 + 30)/3 = 27$

- Can we do better?
FCFS continued

- Suppose we scheduled P2, P3, then P1
  - Would get:

<table>
<thead>
<tr>
<th>T</th>
<th>P_1</th>
<th>P_2</th>
<th>P_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>3</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Throughput: 3 jobs / 30 sec = 0.1 jobs/sec
- Turnaround time:
  - P1: 30
  - P2: 3
  - P3: 6
  - Average TT: (30 + 3 + 6) / 3 = 13 – much less than 27
- Lesson: scheduling algorithm can reduce TT
  - Minimizing waiting time can improve RT and TT
- What about throughput?

View CPU and I/O devices the same

- CPU is one of several devices needed by users’ jobs
  - CPU runs compute jobs, Disk drive runs disk jobs, etc.
  - With network, part of job may run on remote CPU
- Scheduling 1-CPU system with n I/O devices like scheduling asymmetric n + 1-CPU multiprocessor
  - Result: all I/O devices + CPU busy \(\Rightarrow n+1\) fold speedup!

Bursts of computation & I/O

- Jobs contain I/O and computation
  - Bursts of computation
  - Then must wait for I/O
- To Maximize throughput
  - Must maximize CPU utilization
  - Also maximize I/O device utilization
- How to do?
  - Overlap I/O & computation from multiple jobs
  - Means response time very important for I/O-intensive jobs: I/O device will be idle until job gets small amount of CPU to issue next I/O request

Histogram of CPU-burst times

- What does this mean for FCFS?

FCFS Convoy effect

- CPU bound jobs will hold CPU until exit or I/O (but I/O rare for CPU-bound thread)
  - Long periods where no I/O requests issued, and CPU held
  - Result: poor I/O device utilization
- Example: one CPU-bound job, many I/O bound
  - CPU bound runs (I/O devices idle)
  - CPU bound blocks
  - I/O bound job(s) run, quickly block on I/O
  - CPU bound runs again
  - I/O completes
  - CPU bound job continues while I/O devices idle
- Simple hack: run process whose I/O completed?
  - What is a potential problem?

SJF Scheduling

- Shortest-job first (SJF) attempts to minimize TT
  - Schedule the job whose next CPU burst is the shortest
- Two schemes:
  - Non-preemptive – once CPU given to the process it cannot be preempted until completes its CPU burst
  - Preemptive – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt (Know as the Shortest-Remaining-Time-First or SRTF)
- What does SJF optimize?
SJF Scheduling

- **Shortest-job first (SJF)** attempts to minimize TT
  - Schedule the job whose next CPU burst is the shortest

- **Two schemes:**
  - *Non-preemptive* – once CPU given to the process it cannot be preempted until completes its CPU burst
  - *Preemptive* – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt (Know as the Shortest-Remaining-Time-First or SRTF)

- What does SJF optimize?
  - Gives minimum average waiting time for a given set of processes

Examples

<table>
<thead>
<tr>
<th>Process</th>
<th>Arrival Time</th>
<th>Burst Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>0.0</td>
<td>7</td>
</tr>
<tr>
<td>P₂</td>
<td>2.0</td>
<td>4</td>
</tr>
<tr>
<td>P₃</td>
<td>4.0</td>
<td>1</td>
</tr>
<tr>
<td>P₄</td>
<td>5.0</td>
<td>4</td>
</tr>
</tbody>
</table>

- **Non-preemptive**

- **Preemptive**

Drawbacks?

SJF limitations

- Doesn’t always minimize average turnaround time
  - Only minimizes waiting time, which minimizes response time
  - Example where turnaround time might be suboptimal?

- Can lead to unfairness or starvation

- In practice, can’t actually predict the future

- But can estimate CPU burst length based on past
  - Exponentially weighted average a good idea
  - $t_n$ actual length of proc’s $n^{th}$ CPU burst
  - $\tau_{n+1}$ estimated length of proc’s $n + 1^{st}$
  - Choose parameter $\alpha$ where $0 < \alpha \leq 1$
  - Let $\tau_{n+1} = \alpha t_n + (1 - \alpha) \tau_n$

Exp. weighted average example

Round robin (RR) scheduling

- Solution to fairness and starvation
  - Preempt job after some time slice or quantum
  - When preempted, move to back of FIFO queue
  - (Most systems do some flavor of this)

- Advantages:
  - Fair allocation of CPU across jobs
  - Low average waiting time when job lengths vary
  - Good for responsiveness if small number of jobs

- Disadvantages?
RR disadvantages

- Varying sized jobs are good
  ...but what about same-sized jobs?
- Assume 2 jobs of time=100 each:
  - What is average completion time?
  - How does that compare to FCFS?

Context switch costs

- What is the cost of a context switch? (recall from Lecture 2)
- Brute CPU time cost in kernel
  - Save and restore registers, etc.
  - Switch address spaces (expensive instructions)
- Indirect costs: cache, buffer cache, & TLB misses

Time quantum

- How to pick quantum?
  - Want much larger than context switch cost
  - Majority of bursts should be less than quantum
  - But not so large system reverts to FCFS
- Typical values: 10–100 msec

Two-level scheduling

- Switching to swapped out process very expensive
  - Swapped out process has most pages on disk
  - Will have to fault them all in while running
  - One disk access costs ~10ms. On 1GHz machine, 10ms = 10 million cycles!
- Context-switch-cost aware scheduling
  - Run in-core subset for “a while”
  - Then swap some between disk and memory
- How to pick subset? How to define “a while”?
  - View as scheduling memory before CPU
  - Swapping in process is cost of memory “context switch”
  - So want “memory quantum” much larger than swapping cost
Priority scheduling

- Associate a numeric priority with each process
  - E.g., smaller number means higher priority (Unix/BSD)
  - Or smaller number means lower priority (Pintos)
- Give CPU to the process with highest priority
  - Can be done preemptively or non-preemptively
- Note SJF is a priority scheduling where priority is the predicted next CPU burst time
- Starvation – low priority processes may never execute
- Solution?
  - Aging - increase a process’s priority as it waits

Multilevel feedback queues (BSD)

- Every runnable process on one of 32 run queues
  - Kernel runs process on highest-priority non-empty queue
  - Round-robins among processes on same queue
- Process priorities dynamically computed
  - Processes moved between queues to reflect priority changes
  - If a process gets higher priority than running process, run it
- Idea: Favor interactive jobs that use less CPU

Sleeping process increases priority

- p_estcpu not updated while asleep
  - Instead p_slptime keeps count of sleep time
- When process becomes runnable
  \[ p_{estcpu} \leftarrow \left( \frac{2 \cdot \text{load}}{2 \cdot \text{load} + 1} \right) p_{slptime} \times p_{estcpu} \]
  - Approximates decay ignoring nice and past loads
- Previous description based on [McKusick] (The Design and Implementation of the 4.4BSD Operating System)

Process priority

- p_nice – user-settable weighting factor
- p_estcpu – per-process estimated CPU usage
  - Incremented whenever timer interrupt found proc. running
  - Decayed every second while process runnable
  \[ p_{estcpu} \leftarrow \left( \frac{2 \cdot \text{load}}{2 \cdot \text{load} + 1} \right) p_{estcpu} + p_{nice} \]
  - Load is sampled average of length of run queue plus short-term sleep queue over last minute
- Run queue determined by \( p_{usrpri} / 4 \)
  \[ p_{usrpri} \leftarrow 50 + \left( \frac{p_{estcpu}}{4} \right) + 2 \cdot p_{nice} \]
  (value clipped if over 127)

Pintos notes

- Same basic idea for second half of project 1
  - But 64 priorities, not 128
  - Higher numbers mean higher priority
  - Okay to have only one run queue if you prefer (less efficient, but we won’t deduct points for it)
- Have to negate priority equation:
  \[ \text{priority} = 63 - \left( \frac{\text{recent_cpu}}{4} \right) - 2 \cdot \text{nice} \]

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*See library.stanford.edu for off-campus access*
Limitations of BSD scheduler

- Hard to have isolation / prevent interference
  - Priorities are absolute
- Can’t donate priority (e.g., to server on RPC)
- No flexible control
  - E.g., In monte carlo simulations, error is $1/\sqrt{N}$ after $N$ trials
  - Want to get quick estimate from new computation
  - Leave a bunch running for a while to get more accurate results
- Multimedia applications
  - Often fall back to degraded quality levels depending on resources
  - Want to control quality of different streams

Real-time scheduling

- Two categories:
  - Soft real time—miss deadline and CD will sound funny
  - Hard real time—miss deadline and plane will crash
- System must handle periodic and aperiodic events
  - E.g., procs A, B, C must be scheduled every 100, 200, 500 msec, require 50, 30, 100 msec respectively
  - Schedulable if $\sum \frac{CPU}{period} < 1$ (not counting switch time)
- Variety of scheduling strategies
  - E.g., first deadline first (works if schedulable)

Multiprocessor scheduling issues

- Must decide on more than which processes to run
  - Must decide on which CPU to run which process
- Moving between CPUs has costs
  - More cache misses, depending on arch more TLB misses too
- Affinity scheduling—try to keep threads on same CPU
  - But also prevent load imbalances
  - Do cost-benefit analysis when deciding to migrate

Multiprocessor scheduling (cont)

- Want related processes scheduled together
  - Good if threads access same resources (e.g., cached files)
  - Even more important if threads communicate often, otherwise must context switch to communicate
- Gang scheduling—schedule all CPUs synchronously
  - With synchronized quanta, easier to schedule related processes/threads together

Thread scheduling

- With thread library, have two scheduling decisions:
  - Local Scheduling – Thread library decides which user thread to put onto an available kernel thread
  - Global Scheduling – Kernel decides which kernel thread to run next
- Can expose to the user
  - E.g., pthread_attr_setscope allows two choices
    - PTHREAD_SCOPE_SYSTEM – thread scheduled like a process (effectively one kernel thread bound to user thread – Will return ENOTSUP in user-level pthreads implementation)
    - PTHREAD_SCOPE_PROCESS – thread scheduled within the current process (may have multiple user threads multiplexed onto kernel threads)

Thread dependencies

- Say $H$ at high priority, $L$ at low priority
  - $L$ acquires lock $l$.
  - Scene 1: $H$ tries to acquire $l$, fails, spins. $L$ never gets to run.
  - Scene 2: $H$ tries to acquire $l$, fails, blocks. $M$ enters system at medium priority. $L$ never gets to run.
  - Both scenes are examples of priority inversion
- Scheduling = deciding who should make progress
  - Obvious: a thread’s importance should increase with the importance of those that depend on it.
  - Naive priority schemes violate this
Priority donation

- Say higher number = higher priority
- Example 1: L (prio 2), M (prio 4), H (prio 8)
  - L holds lock l
  - M waits on l, L’s priority raised to $L' = \max(M, L) = 4$
  - Then H waits on l, L’s priority raised to $\max(H, L') = 8$
- Example 2: Same threads
  - L holds lock l, M holds lock $l_2$
  - M waits on $l_2$, L’s priority now $L' = 4$ (as before)
  - Then H waits on $l_2$, M’s priority goes to $M' = \max(H, M) = 8$,
    and L’s priority raised to $\max(M', L') = 8$
- Example 3: L (prio 2), $M_1, \ldots, M_{1000}$ (all prio 4)
  - L has l, and $M_1, \ldots, M_{1000}$ all block on l. L’s priority is
    $\max(L, M_1, \ldots, M_{1000}) = 4$.

Packet scheduling

- Differences from CPU scheduling
  - No preemption or yielding—must send whole packets
    - Thus, can’t send one bit at a time
  - But know how many bits are in each packet
    - Can see the future and know how long packet needs link
- What scheduling algorithm does this suggest?

FQ Algorithm

- Suppose clock ticks each time a bit is transmitted
- Let $P_i$ denote the length of packet $i$
- Let $S_i$ denote the time when start to transmit packet $i$
- Let $F_i$ denote the time when finish transmitting packet $i$
  - $F_i = S_i + P_i$
- When does router start transmitting packet $i$?
  - If arrived before router finished packet $i - 1$ from this flow,
    then immediately after last bit of $i - 1$ ($F_{i-1}$)
  - If no current packets for this flow, then start transmitting when
    arrives (call this $A_i$)
- Thus: $F_i = \max(F_{i-1}, A_i) + P_i$

Fair Queuing (FQ)

- Digression: packet scheduling problem
  - Which network packet should router send next over a link?
  - Problem inspired some algorithms we will see next week
  - Plus good to reinforce concepts in a different domain...
- For ideal fairness, would send one bit from each flow
  - In weighted fair queuing (WFQ), more bits from some flows

Packet scheduling

- Differences from CPU scheduling
  - No preemption or yielding—must send whole packets
    - Thus, can’t send one bit at a time
  - But know how many bits are in each packet
    - Can see the future and know how long packet needs link
- What scheduling algorithm does this suggest? SJF
- Recall limitations of SJF:
  - Can’t see the future
    - solved by packet length
  - Optimizes response time, not turnaround time
    - but these are the same when sending whole packets
  - Not fair
- Kind of want fair SJF for networking

FQ Algorithm (cont)

- For multiple flows
  - Calculate $F_i$ for each packet that arrives on each flow
  - Treat all $F_i$’s as timestamps
  - Next packet to transmit is one with lowest timestamp
- Example: