• Remember send email for any course staff to:
cs140-staff@scs.stanford.edu
  - cs140-staff gets priority than my personal mailbox

• Assignment 1 due one week from now

• 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, numbers up this year
  - 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.
• 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?
CPU Scheduling

- Scheduling decisions may take place when a process:
  1. Switches from running to waiting state
  2. Switches from running to ready state
  3. Switches from waiting to ready
  4. Exits

- Non-preemptive schedules use 1 & 4 only
- Preemptive schedulers run at all four points
Scheduling criteria

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

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

• Throughput – # of procs 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:

  \[
  \begin{array}{c|c|c|c}
  \text{P}_1 & \text{P}_2 & \text{P}_3 \\
  0 & 24 & 27 & 30 \\
  \end{array}
  \]

- 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 $P_2$, $P_3$, then $P_1$
  - Would get:

  ![Diagram showing scheduling sequence]

  - Throughput: $3$ jobs / $30$ sec = $0.1$ jobs/sec
  - Turnaround time: $P_1 : 30$, $P_2 : 3$, $P_3 : 6$
    - 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 \( \implies \) \( n+1 \) fold speedup!

- Overlap them just right? throughput will be almost doubled
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

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  - 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
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- **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>$P_1$</td>
<td>0.0</td>
<td>7</td>
</tr>
<tr>
<td>$P_2$</td>
<td>2.0</td>
<td>4</td>
</tr>
<tr>
<td>$P_3$</td>
<td>4.0</td>
<td>1</td>
</tr>
<tr>
<td>$P_4$</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

<table>
<thead>
<tr>
<th>CPU burst ($t_i$)</th>
<th>6</th>
<th>4</th>
<th>6</th>
<th>4</th>
<th>13</th>
<th>13</th>
<th>13</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;guess&quot; ($\tau_i$)</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>9</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>
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)
Context switch costs

- What is the cost of a context switch?
- 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**
Turnaround time vs. quantum

<table>
<thead>
<tr>
<th>process</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>6</td>
</tr>
<tr>
<td>$P_2$</td>
<td>3</td>
</tr>
<tr>
<td>$P_3$</td>
<td>1</td>
</tr>
<tr>
<td>$P_4$</td>
<td>7</td>
</tr>
</tbody>
</table>
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 $\sim 10\text{ms}$. On 1GHz machine, $10\text{ms} = 10$ 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?
Priority scheduling

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- 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-robin 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
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** \( p_{uspri}/4 \)

\[
p_{uspri} \leftarrow 50 + \left( \frac{p_{estcpu}}{4} \right) + 2 \cdot p_{nice}
\]

(value clipped if over 127)
Sleeping process increases priority

- \( p_{estcpu} \text{ not updated while asleep} \)
  - 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]\(^a\)

\(^a\)See library.stanford.edu for off-campus access
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:

\[
\text{priority} = 63 - \left(\frac{\text{recent_cpu}}{4}\right) - 2 \cdot \text{nice}
\]
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 \( \sum \frac{CPU}{period} \leq 1 \) (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.
  - Naïve 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 $l$, $L$’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 $\max(L, M_1, \ldots, M_{1000}) = 4$. 
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?
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

- 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**: $F_i = \max(F_{i-1}, A_i) + P_i$
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: