CS 318 Principles of Operating Systems

Fall 2020

Lecture 5: Scheduling

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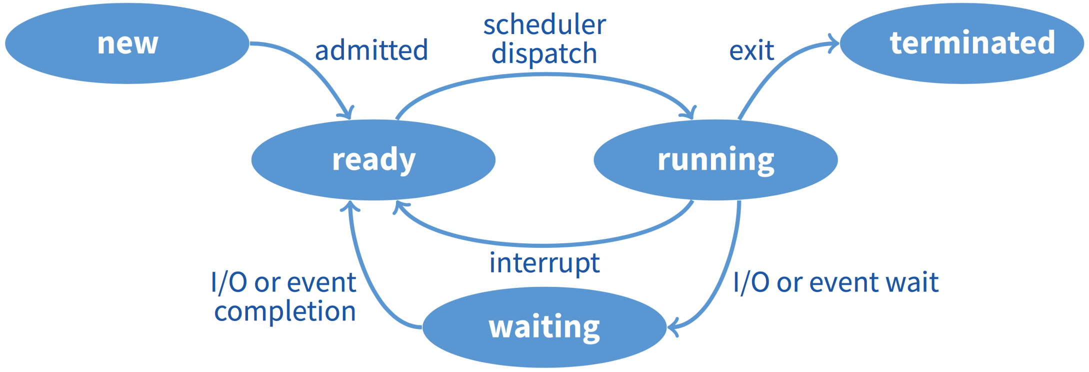
Administrivia

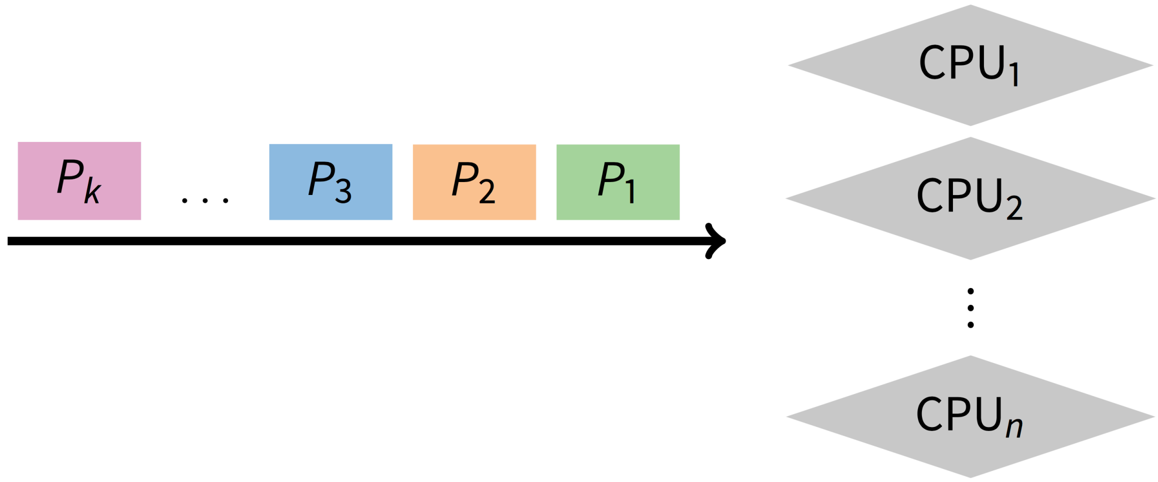
- **New CA: Stephen Kyranakis**
  - Office hour Mon 9-10am, Thu 9-10am ET
- **Attend office hours to get help**
  - Don’t wait until the lab deadline to seek help
  - OK (encouraged) to check your design/algorithm with TAs/instructor
- **Lab 1 released**
  - Due in two weeks
  - Lab overview session Wednesday 8-9pm EDT
  - If you still don’t have a group, let us know ASAP
  - GitHub classroom invitation link on Piazza post

Recap: Processes, Threads

- **Process is the OS abstraction for execution**
  - own view of machine
- **Process components**
  - address space, program counter, registers, open files, etc.
  - kernel data structure: Process Control Block (PCB)
- **Process vs. thread**
- **Process/thread states and APIs**
  - state graph and queues
  - process creation, deletion, waiting
- **Multiple processes/threads**
  - overlapping I/O and CPU activities
  - context switch



Scheduling Overview

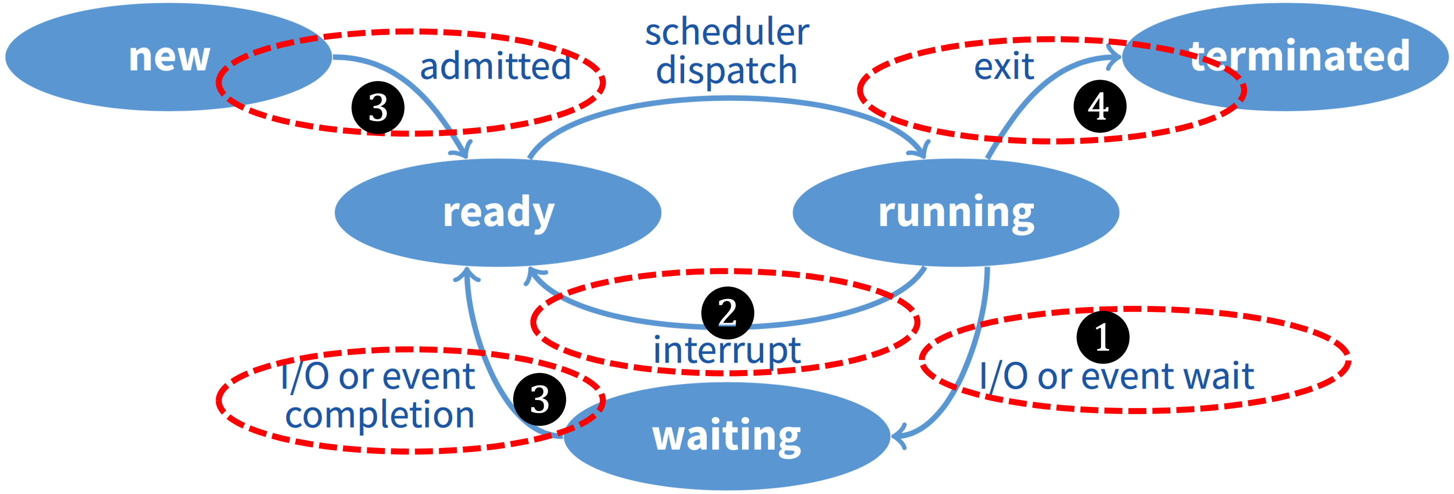


- **The scheduling problem:**
  - Have K jobs ready to run
  - Have $N \geq 1$ CPUs
- **Policy: which jobs should we assign to which CPU(s), for how long?**
  - we'll refer to schedulable entities as jobs – could be processes, threads, people, etc.
- **Mechanism: context switch, process state queues**

Scheduling Overview

1. **Goals of scheduling**
2. **Textbook scheduling**
3. **Priority scheduling**
4. **Advanced scheduling topics (not required)**

When Do We Schedule CPU?



- **Scheduling decisions may take place when a process:**
  ❶ Switches from running to waiting state
  ❷ Switches from running to ready state
  ❸ Switches from new/waiting to ready
  ❹ Exits

- **Non-preemptive schedules use ❶ & ❹ only**

- **Preemptive schedulers run at all four points**

Scheduling Goals

- **Scheduling works at two levels in an operating system**
  - To determine the multiprogramming level – # of jobs loaded into memory
    - Moving jobs to/from memory is often called swapping
  - To decide what job to run next to guarantee "good service"
    - Good service could be one of many different criteria
- **Known as long-term and short-term scheduling decisions**
  - Long-term scheduling happens relatively infrequently (Virtual memory lecture)
    - Significant overhead in swapping a process out to disk
  - Short-term scheduling happens relatively frequently (this lecture)
    - Want to minimize the overhead of scheduling
      - Fast context switches, fast queue manipulation

Scheduling “Non-goal”: Starvation

- **Starvation is when a process is prevented from making progress because some other process has the resource it requires**
  - Resource could be the CPU, or a lock (recall readers/writers)
- **Starvation usually a side effect of the sched. algorithm**
  - A high priority process always prevents a low priority process from running
  - One thread always beats another when acquiring a lock
- **Starvation can be a side effect of synchronization**
  - Constant supply of readers always blocks out writers

Scheduling Criteria

- **Why do we care?**
  - How do we measure the effectiveness of a scheduling algorithm?

Scheduling Criteria

- **Throughput – # of processes that complete per unit time**
  - $\# \; jobs/time$
  - Higher is better
- **Turnaround time – time for each process to complete**
  - $T_{finish} - T_{start}$
  - Lower is better
- **Response time – time from request to *first* response**
  - $T_{response} - T_{request}$ i.e., , time between *waiting*→ *ready* transition and *ready*→ *running*
    - e.g., key press to echo, not launch to exit
  - Lower is better
- **Above criteria are affected by secondary criteria**
  - *CPU utilization* – $\%CPU$ fraction of time CPU doing productive work
  - *Waiting time* – $Avg(T_{wait})$ time each process waits in the ready queue

What Criterial Should We Use?

- **Batch systems**
  - Strive for job throughput, turnaround time (supercomputers)
- **Interactive systems**
  - Strive to minimize response time for interactive jobs (PC)
    - Utilization and throughput are often traded off for better response time
- **Usually optimize average measure**
  - Sometimes also optimize for min/max or variance
    - e.g., minimize the maximum response time
    - e.g., users prefer predictable response time over faster but highly variable response time

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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:

- **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
- **Waiting Time: P_1 : 0, P_2 : 24, P_3 : 27**
  - Average WT: (0 + 24 + 27) / 3 = 17
- **Can we do better?**

FCFS Continued

- **Suppose we scheduled P_2, P_3, then P_1**
  - Would get:

- **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
- **Can a scheduling algorithm improve throughput?**
  - Yes, if jobs require both computation and I/O

FCFS Limitations

- **FCFS algorithm is non-preemptive in nature**
  - Once CPU time has been allocated to a process, other processes can get CPU time only after the current process has finished or gets blocked.
- **This property of FCFS scheduling is called *Convoy Effect***

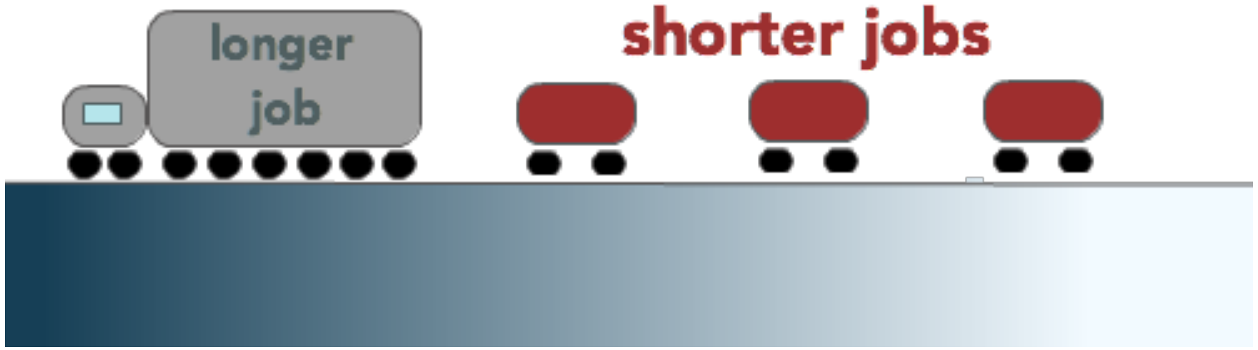


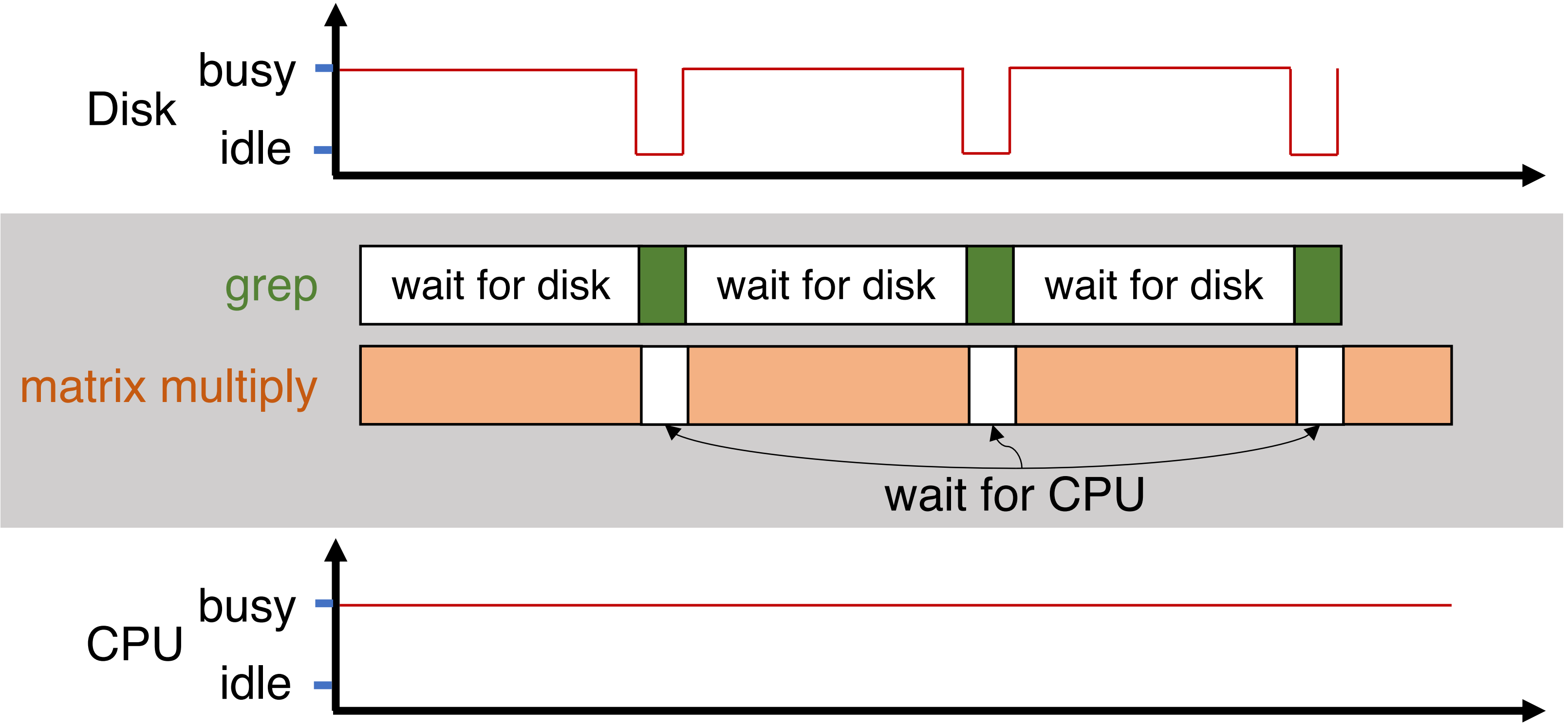
image source: http://web.cs.ucla.edu/classes/fall14/cs111/scribe/7a/convoy_effect.png

Scheduling Jobs with Computation & I/O (1)

- **Can a scheduling algorithm improve throughput?**
  - Yes, if jobs require both computation and I/O
- **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 ➔ $(n+1)$-fold throughput gain!

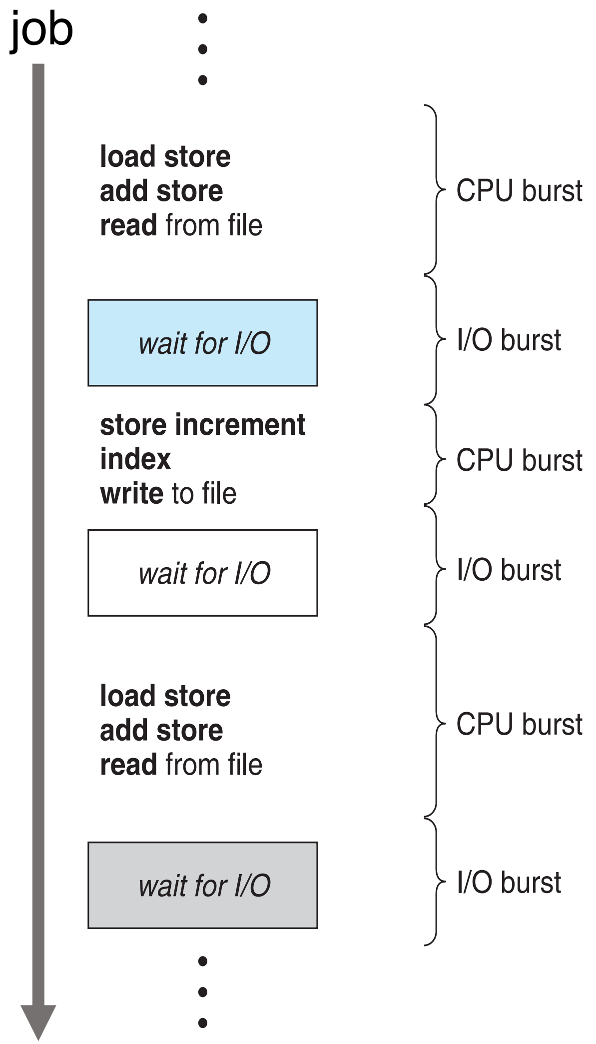
Scheduling Jobs with Computation & I/O (2)

- **Example: disk-bound** `grep` **+ CPU-bound** `matrix_multiply`
  - Overlap them just right, throughput will be almost doubled

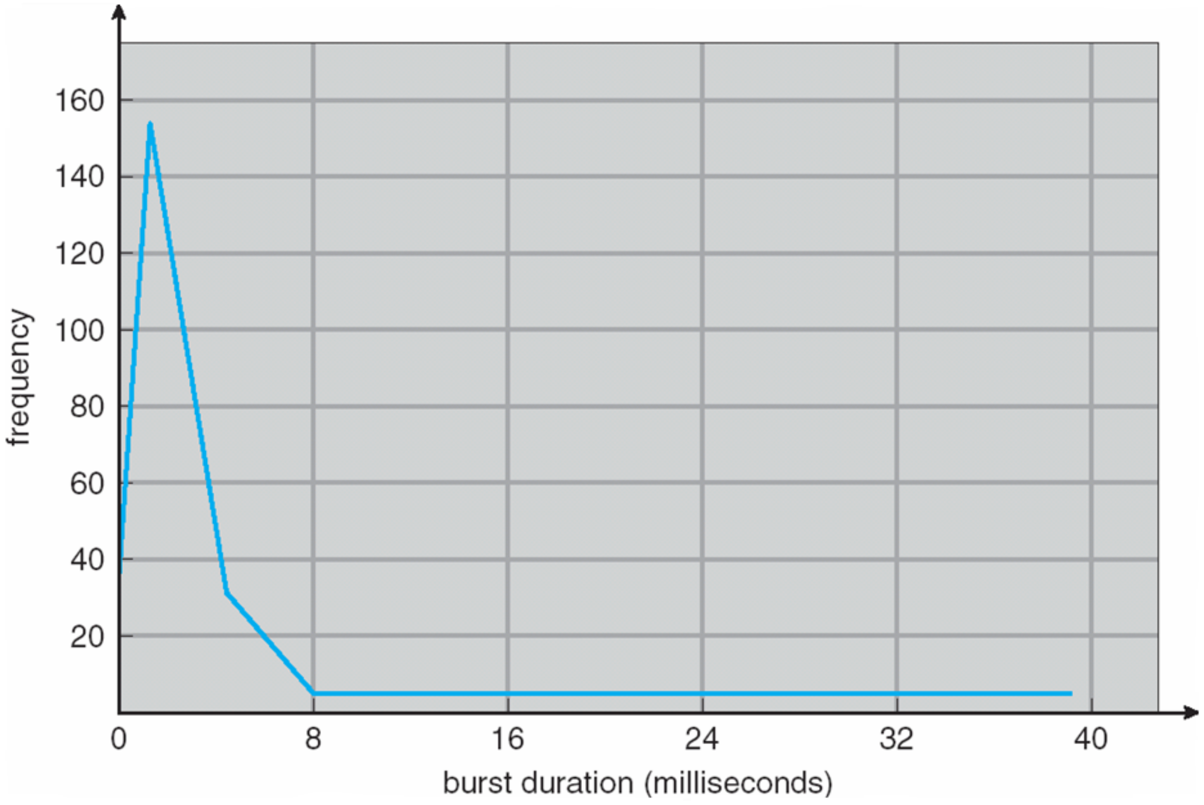


Bursts of Computation & I/O

- **The previous example is not a corner case!**
- **Lots of jobs contain both I/O and computation**
  - Bursts of computation
  - Then must wait for I/O
- **Goal: maximize throughput**
  - maximize both CPU and I/O device utilization
- **How?**
  - Overlap computation from one job with I/O from other jobs



Histogram of CPU-burst Times

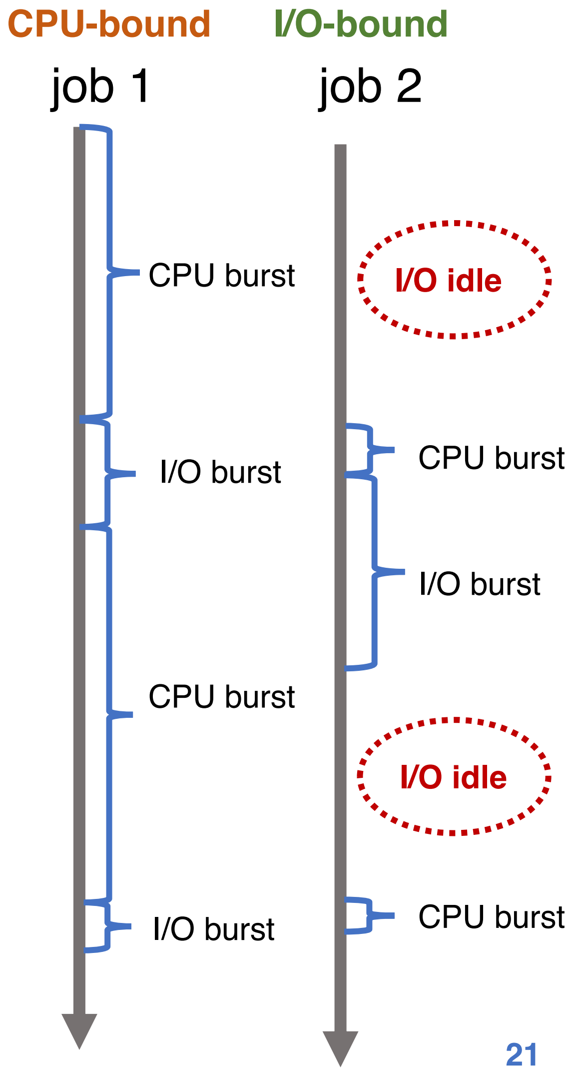


- Most jobs have short CPU burst
- A few jobs have very long CPU burst

- **What does this mean for FCFS?**

FCFS Convoy Effect

- **CPU-bound jobs will hold CPU until exit or I/O**
  - But CPU-bound job's I/O burst is small
  - 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**
  1. CPU-bound job runs (I/O devices idle)
  2. Eventually, CPU-bound job blocks on I/O
  3. I/O-bound jobs run, but each quickly blocks on I/O
  4. CPU-bound job unblocks, runs again
  5. All I/O requests complete, but CPU-bound job still hogs CPU
  6. I/O devices sit idle since I/O-bound jobs can't issue next requests



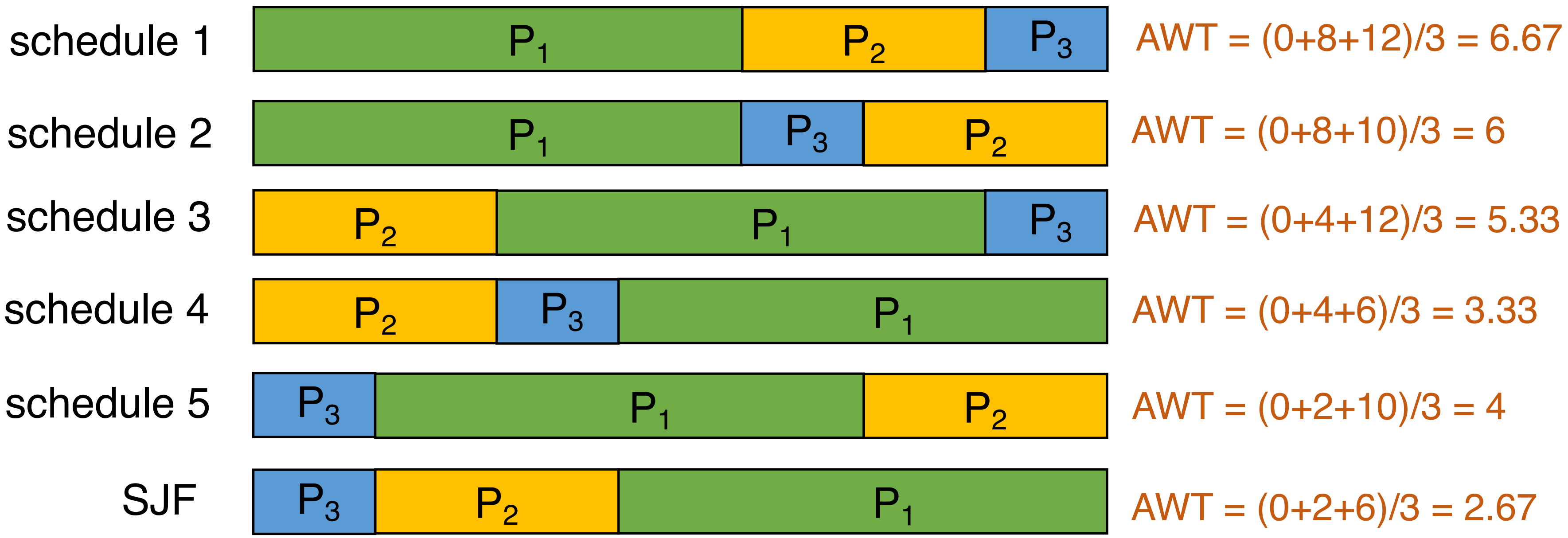
Shortest Job First (SJF)

- **Shortest Job First (SJF)**
  - Choose the job with the smallest expected CPU burst
    - Person with smallest # of items in shopping cart checks out first
- **Example**
  - Three jobs available, CPU bursts are P_1 8 sec, P_2 4 sec, P_3 2 sec

Average Waiting Time: (0 + 2 + 6) / 3 = 2.67

SJF Has Optimal Average Waiting Time

- **SJF has *provably* optimal minimum average *waiting* time (AWT)**
- **Previous example: P_1 8 sec, P_2 4 sec, P_3 2 sec**
  - How many possible schedules?



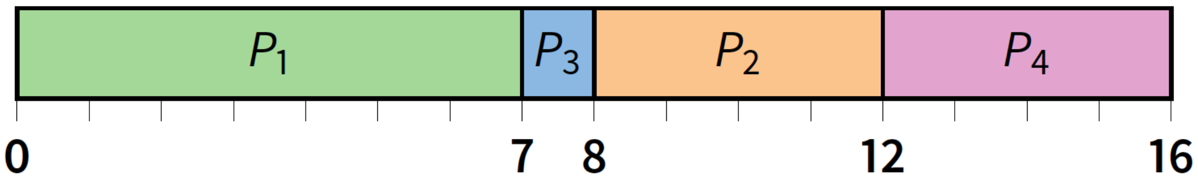
Shortest Job First (SJF)

- **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 current process
    - Known as the *Shortest-Remaining-Time-First* or ***SRTF***

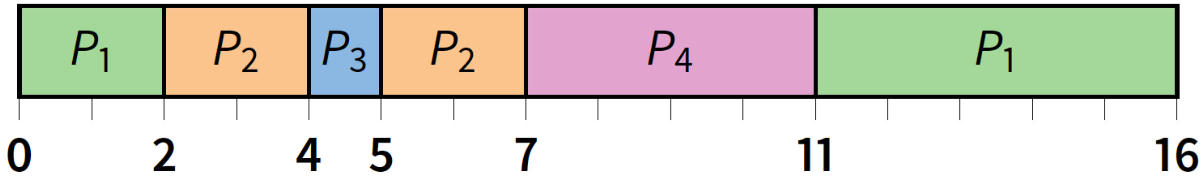
Examples

Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4

- **Non-preemptive**



- **Preemptive**

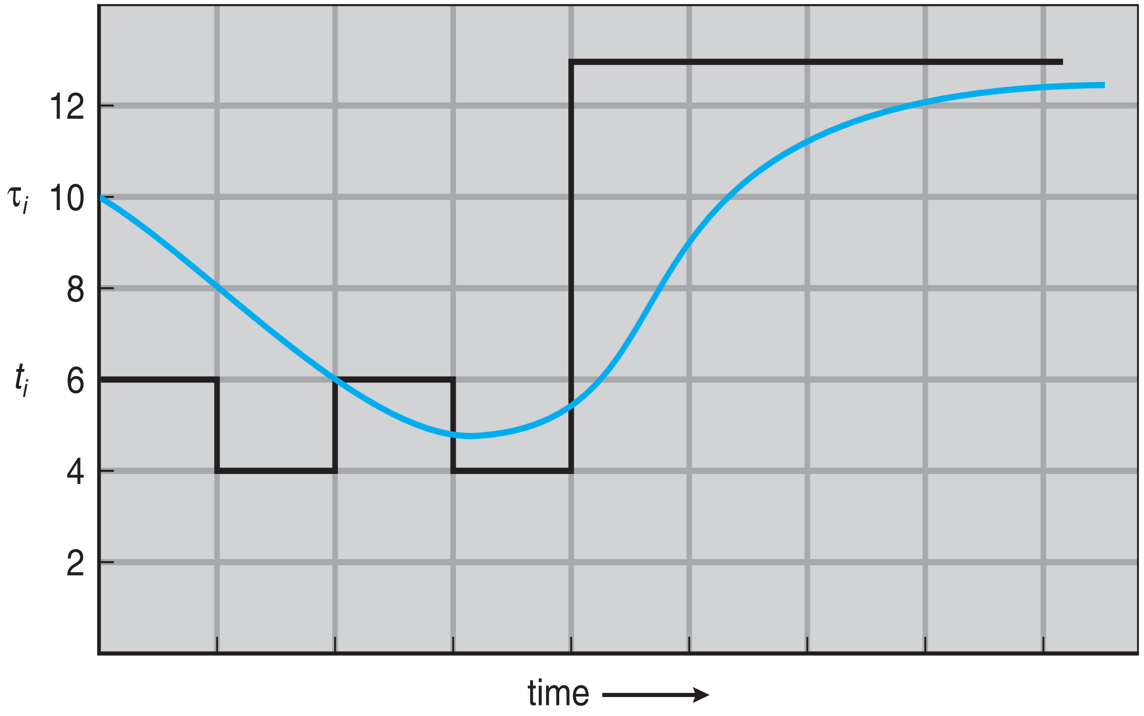


What is the AWT?

SJF Limitations

- **Doesn't always minimize average TT**
  - Only minimizes waiting time
  - Example where turnaround time might be suboptimal?
- **Can potentially lead to unfairness or starvation**
- **Impossible to know size of CPU burst ahead of time**
  - Like choosing person in line without looking inside cart
- **How can you make a reasonable guess?**
  - Estimate CPU burst length based on past
  - E.g., exponentially weighted average
    - t_n actual length of process's n^{th} CPU burst
    - τ_{n+1} estimated length of proc's $(n+1)^{st}$ CPU burst
    - Choose parameter α where $0 < \alpha \leq 1$, e.g., $\alpha = 0.5$
    - Let $\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n$

Exp. Weighted Average Example



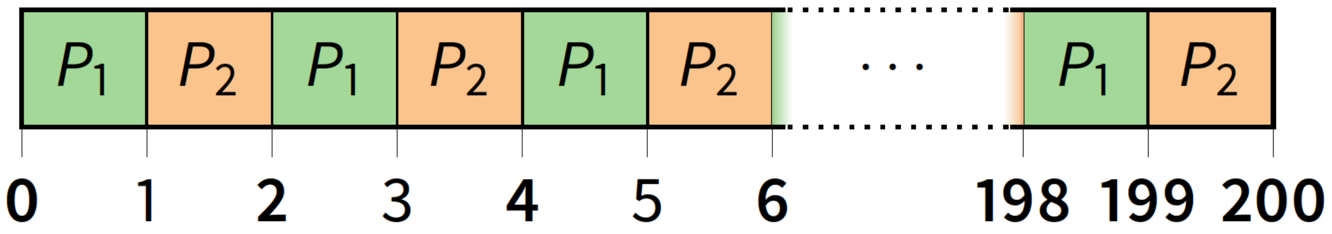
CPU burst (t_i)		6	4	6	4	13	13	13	…
"guess" (τ_i)	10	8	6	6	5	9	11	12	…

Round Robin (RR)

- **Solution to fairness and starvation**
  - Each job is given a time slice called a quantum
  - Preempt job after duration of quantum
  - When preempted, move to back of FIFO queue
- **Advantages:**
  - Fair allocation of CPU across jobs
  - Low average waiting time when job lengths vary
  - Good for responsiveness if small number of jobs
- **Disadvantages?**

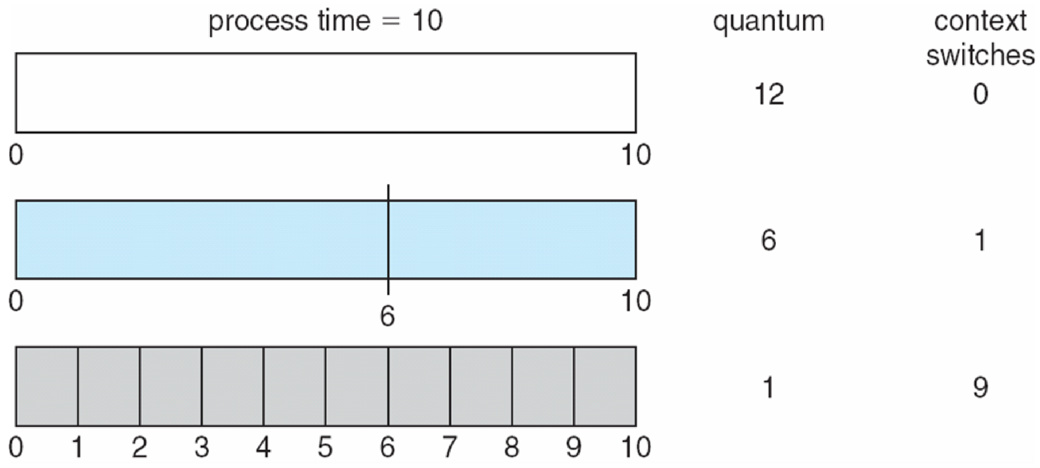
RR Disadvantages

- **Context switches are frequent and need to be very fast**
- **Varying sized jobs are good …what about same-sized jobs?**
- **Assume 2 jobs of time=100 each:**



- **Even if context switches were free…**
  - What would average turnaround time be with RR?
  - How does that compare to FCFS?

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: 1–100** msec

Scheduling Overview

1. Goals of scheduling
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4. **Advanced scheduling topics (not required)**

Priority Scheduling

- **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
    - Airline check-in for first class passengers
    - Can be done preemptively or non-preemptively
  - Can implement SJF, priority = 1/(expected CPU burst)
- **Problem: starvation – low priority jobs can wait indefinitely**
- **Solution? "Age" processes**
  - Increase priority as a function of waiting time
  - Decrease priority as a function of CPU consumption

Priority Inversion

- **Caveat using Priority Scheduling w/ Synch Primitives**
  - Priority scheduling Rule
    - Always pick highest-priority thread
    - …*unless* a lower-priority thread is holding a resource the highest-priority thread wants to get
  - Potential *Priority Inversion* Problem
- **Two tasks: *H* at high priority, *L* at low priority**
  - *L* acquires lock `k` for exclusive use of a shared resource R
  - If *H* tries to acquire `k`, blocked until *L* release resource R
  - *M* enters system at medium priority, preempts *L*
    - *L* unable to release R in time
    - *H* unable to run, despite having higher priority than *M*
- **Not just a hypothetical issue, it happened in real-world software!**
  - The root cause for a famous Mars PathFinder failure in 1997
  - low-priority data gathering task and a medium-priority communications task prevented the critical bus management task from running

Solution: Priority Donation

- **"Donate" our priority if we get blocked**
  - Whenever a high-priority task has to wait for some shared resource that currently held by an executing low priority task,
  - the low-priority task is *temporarily* assigned the priority of the highest waiting priority task for the duration of its use of the shared resource

- **Why this helps?**
  - Since the low-priority task gets temporarily boosted priority, it keeps medium priority tasks from pre-empting the (originally) low priority task
  - Once resource released, low-priority task continues at its original priority

Priority Donation Example

- **Say higher number = higher priority (like Pintos)**

- **Example 1: *L* (prio 2), *M* (prio 4), *H* (prio 8)**
  - *L* holds lock `k`
  - *M* waits on `k`, *L*'s priority raised to $L_1 = \max(M; L) = 4$
  - Then *H* waits on `k`, *L*'s priority raised to $\max(H; L_1) = 8$

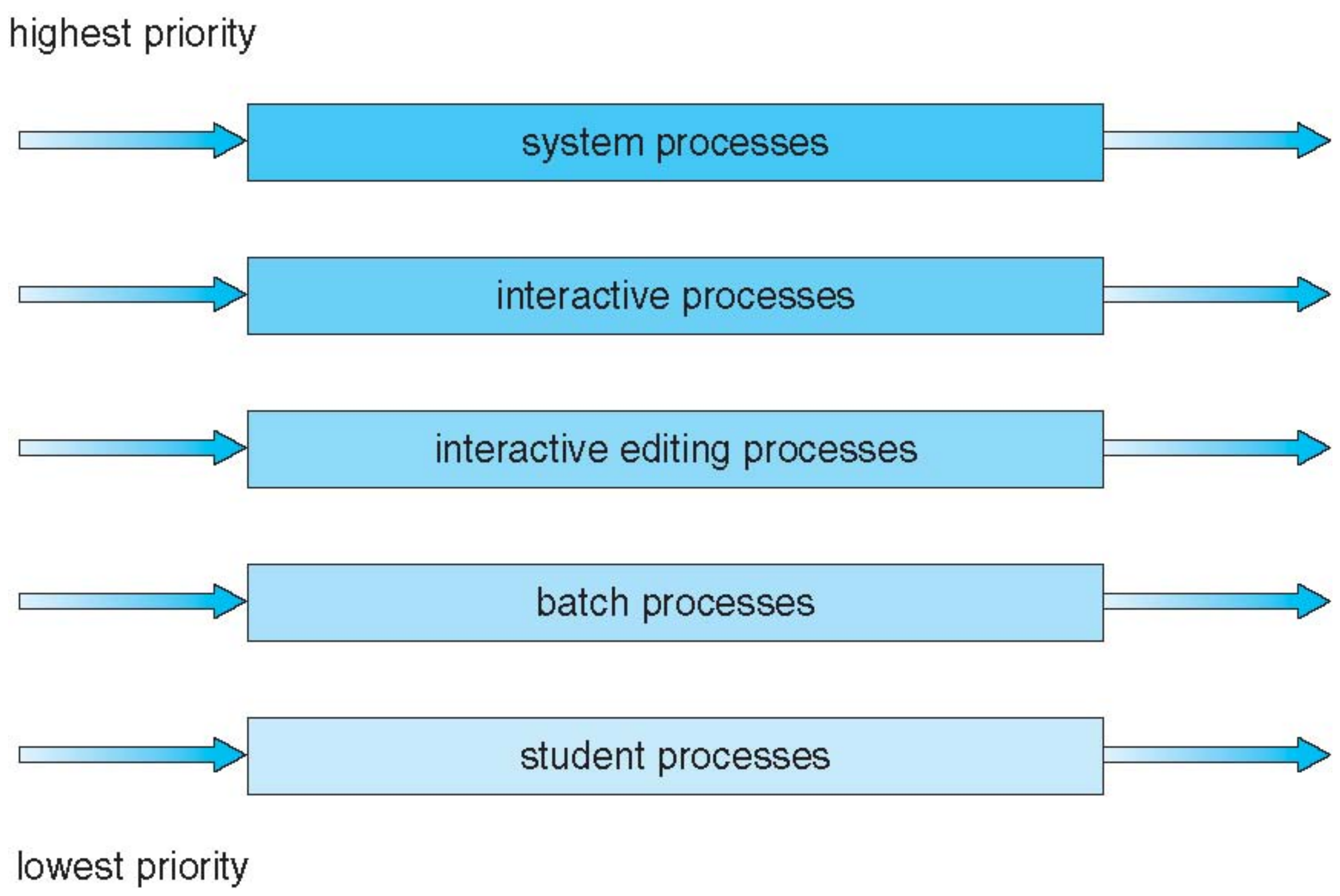
- **Example 2: Same *L*, *M* , *H* as above**
  - *L* holds lock `k`, *M* holds lock $\texttt{k}_2$
  - *M* waits on `k`, *L*'s priority now $L_1 = 4$ (as before)
  - Then *H* waits on $\texttt{k}_2$
    - *M'*s priority goes to $M_1 = \max(H; M) = 8$, and *L*'s priority raised to $\max(M_1; L_1) = 8$

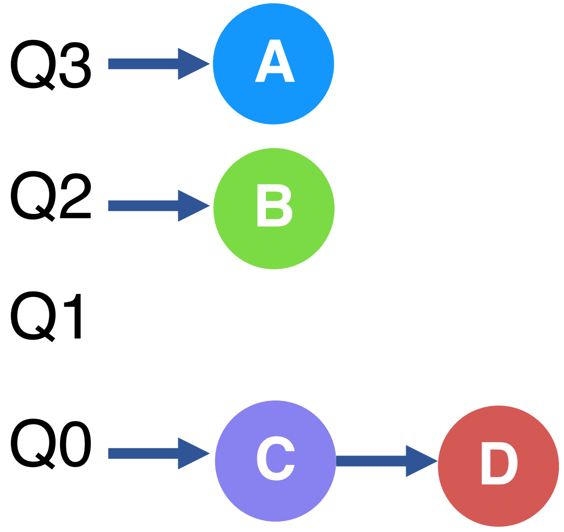
- **Pintos Lab 1 Exercise 2.2**

Combining Algorithms

- **Different types of jobs have different preferences**
  - Interactive, CPU-bound, batch, system, etc.
  - Hard to use one size to fit all
- **Combining scheduling algorithms to optimize for multiple objectives**
  - Have multiple queues
  - Use a different algorithm for each queue
  - Move processes among queues
- **Example: Multiple-level feedback queues (MLFQ)**
  - Multiple queues representing different job types
  - Queues have priorities
    - Job in higher-priority queue can preempt jobs lower-priority queue
  - Jobs on same queue use the same scheduling algorithm, typically RR

Multilevel Queue Scheduling



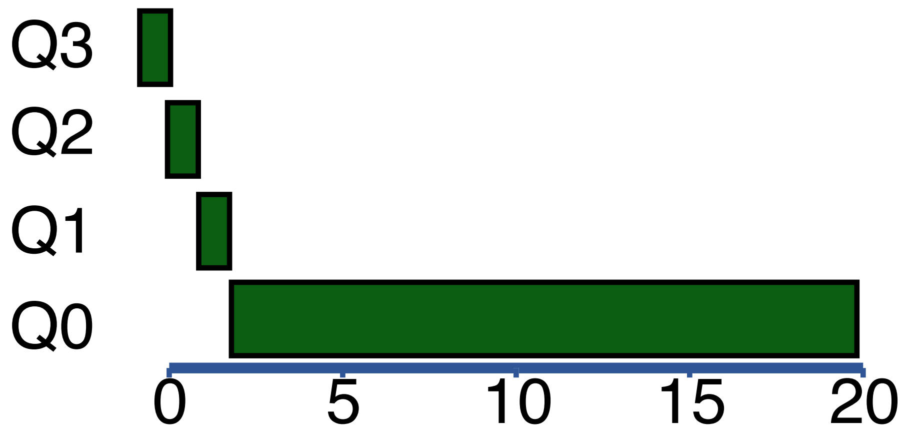


MLFQ

- **Goal #1: Optimize job turnaround time for “batch” jobs**
  - Shorter jobs run first
  - Why not SJF?
- **Goal #2: Minimize response time for “interactive” jobs**
- **Challenge:**
  - No *a priori knowledge* of what type a job is, what the next burst is, etc.
  - Let a job tells us its “niceness” (priority)?
- **Idea:**
  - Change a process’s priority based on how it behaves in the past (history “feedback”)

MLFQ: How to Change Priority Over Time?

- **Attempt**
  - *Rule A*: Processes start at top priority
  - *Rule B*: If job uses whole slice, demote process
    - i.e., longer time slices at lower priorities
  - Example 1: A long-running “batch” job



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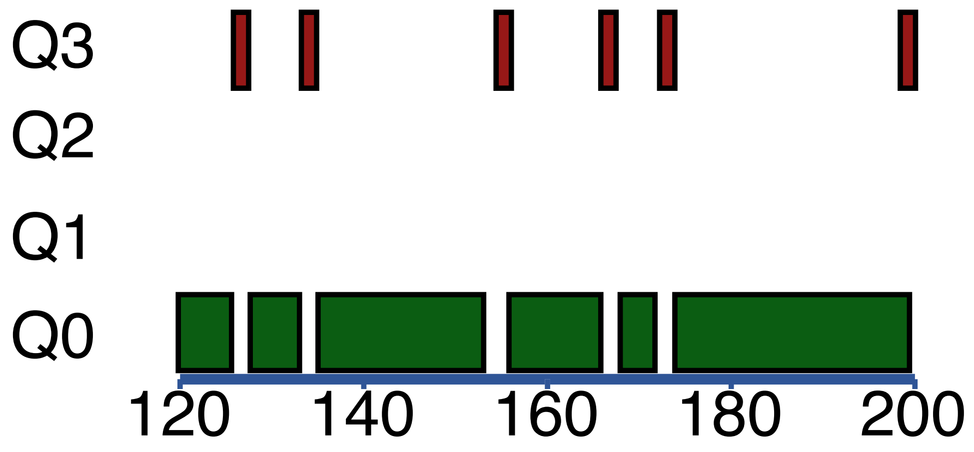
  - Example 1: A long-running “batch” job
  - Example 2: An “interactive” job comes along



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  - *Rule A*: Processes start at top priority
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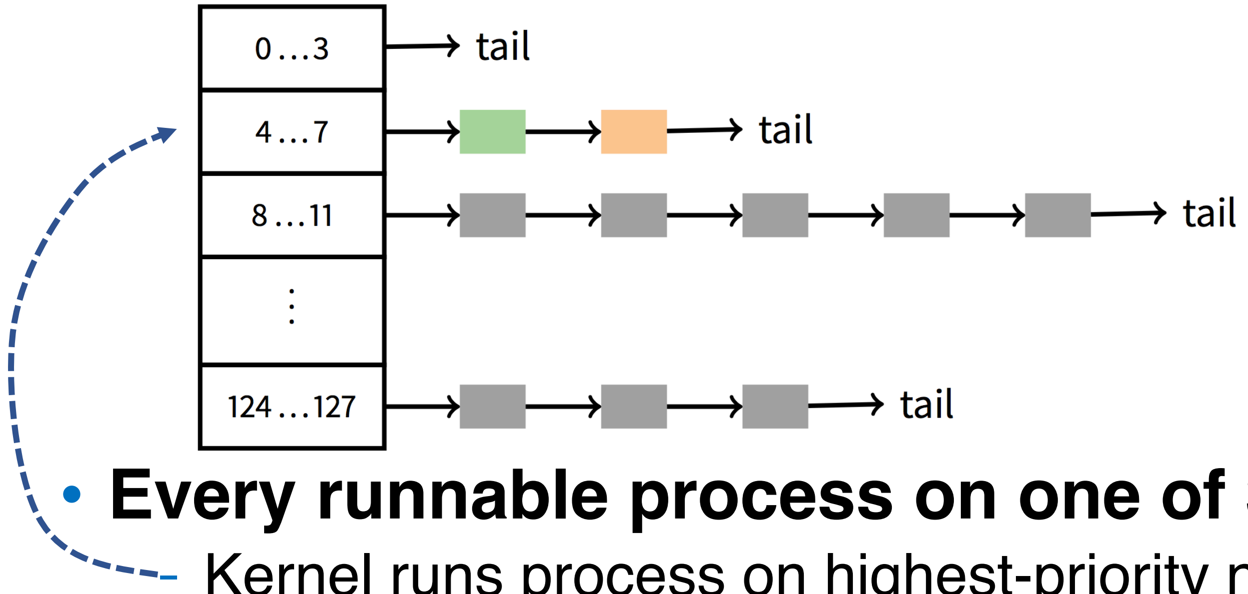
  - Example 1: A long-running “batch” job
  - Example 2: An “interactive” job comes along
  - **Problems:**
    - unforgiving + starvation
    - gaming the system
      - E.g., performing I/O right before time-slice ends

MLFQ: How to Change Priority Over Time?

- **Attempt**
  - *Rule A*: Processes start at top priority
  - *Rule B*: If job uses whole slice, demote process
  - Example 1: A long-running “batch” job
  - Example 2: An “interactive” job comes along
  - **Problems:**
    - unforgiving + starvation
    - gaming the system
- **Fixing the problems**
  - Periodically boost priority for jobs that haven’t been scheduled
  - Account for job’s *total* run time at priority level (instead of just this time slice)

MLFQ in 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
- **Favor interactive jobs that use less CPU**

Process Priority Calculation in BSD

- `p_nice` **– user-settable weighting factor, value range [-20, 20]**
- `p_estcpu` **– per-process estimated CPU usage**
- **Process priority** `p_usrpri`
  - $$p\_usrpri \leftarrow 50 + \left(\frac{p\_estcpu}{4}\right) + 2 * p\_nice$$

    Rationale: *decrease* priority linearly based on recent CPU
  - Calculated every 4 ticks, values are bounded to [50, 127]
- **How to calculate** `p_estcpu` **?**
  - Incremented whenever timer interrupt found process running
  - Decayed every second while process runnable

$$p\_estcpu \leftarrow \left(\frac{2 * load}{2 * load + 1}\right) * p\_estcpu + p\_nice$$

  - Load is sampled average of length of run queue plus short-term sleep queue over last minute

Sleeping Process Increases Priority

- `p_estcpu` **not updated while asleep**
  - Instead `p_slptime` keeps count of sleep time
- **When process becomes runnable**

$$p\_estcpu \leftarrow \left(\frac{2 \; * \; load}{2 * load + 1}\right)^{p\_slptime} * \; p\_estcpu$$

  - Approximates decay ignoring nice and past loads
- **Description based on "*The Design and Implementation of the 4.4BSD Operating System*"**

Pintos Notes

- **Same basic idea for second half of Lab 1**
  - But 64 priorities, not 128
  - Higher numbers mean higher priority (in BSD, higher num means lower prio)
  - 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:**
  - Formula in BSD

$$p\_usrpri \leftarrow 50 + \left(\frac{p\_estcpu}{4}\right) + 2 * p\_nice$$

  - Formula in Pintos

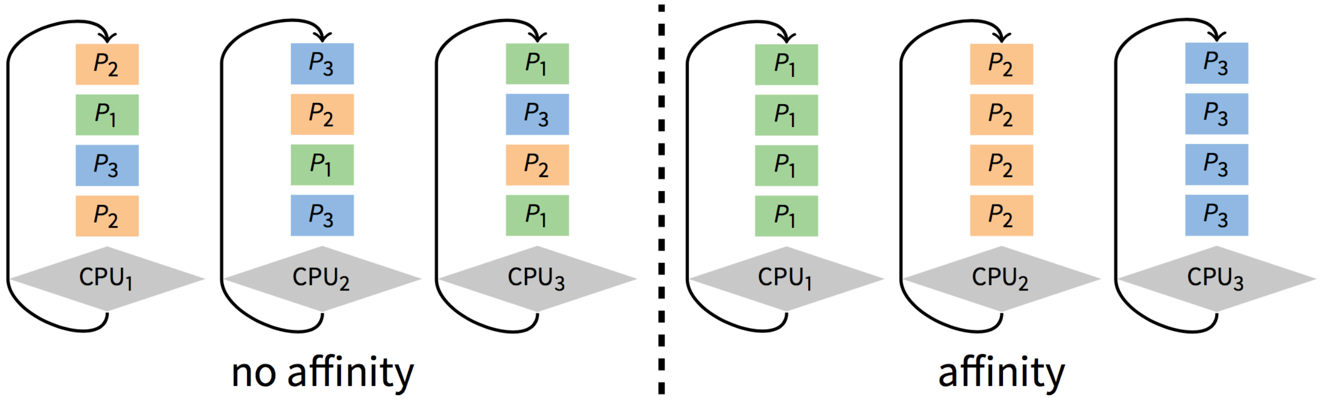
$$priority \leftarrow 63 - \left(\frac{recent\_cpu}{4}\right) - 2 * nice$$

Scheduling Overview

1. Goals of scheduling
2. Textbook scheduling
3. Priority scheduling
4. ~~Advanced scheduling topics~~

Multiprocessor Scheduling Issues

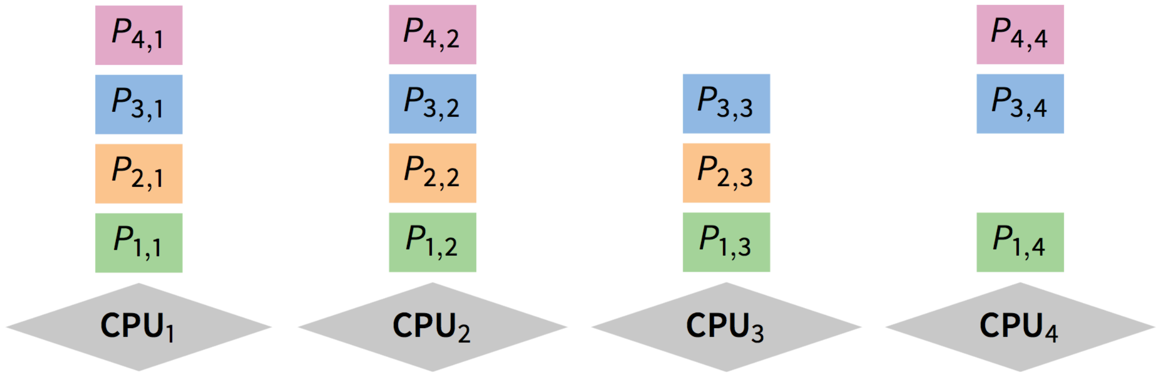
- **Must decide on more than which processes to run**
  - Must decide on which CPU to run which process
- **Moving between CPUs has costs**
  - More cache misses, depending on arch. more TLB misses too
- ***Affinity scheduling*—try to keep process/thread on same CPU**



  - But also prevent load imbalances
  - Do cost-benefit analysis when deciding to migrate...affinity can also be harmful, particularly when tail latency is critical

Multiprocessor Scheduling (cont)

- **Want related processes/threads 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



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., processes A, B, C must be scheduled every 100, 200, 500 msec, require 50, 30, 100 msec respectively
  - *Schedulable* if $\sum \frac{cpu}{period} \leq 1$
- **Variety of scheduling strategies**
  - E.g., first deadline first (works if schedulable, otherwise fails spectacularly)

Scheduling Summary

- **Scheduling algorithm determines which process runs, quantum, priority…**
- **Many potential goals of scheduling algorithms**
  - Utilization, throughput, wait time, response time, etc.
- **Various algorithms to meet these goals**
  - FCFS/FIFO, SJF, RR, Priority
- **Can combine algorithms**
  - Multiple-Level Feedback Queues (MLFQ)
- **Advanced topics**
  - *affinity scheduling, gang scheduling, real-time scheduling*

Next Time

- **Read Chapter 26, 27**