CS 318 Principles of Operating Systems

Fall 2021

Lecture 5: Scheduling

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Administrivia

Lab 1 released

- If you still don't have a group, let us know ASAP

Attend office hours to get help

- Don't wait until the lab deadline to seek help
- Encouraged to check your design/algorithm with TAs/instructor

I will host a "LOST" session (by appointment) besides office hour

- Personalized for students who found some lecture to be confusing to follow

Recap: Processes, Threads

Process is the OS abstraction for execution

- own view of machine

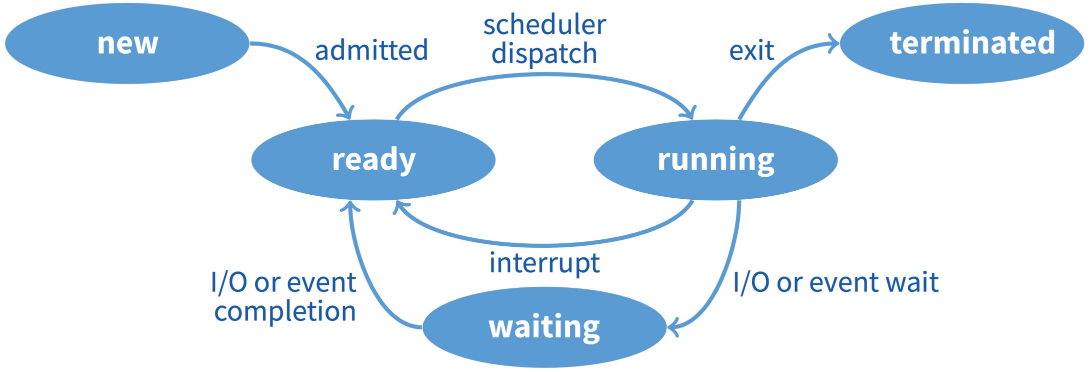
Process components

- address space, program counter, registers, open files, etc.
- kernel data structure: Process Control Block (PCB)

Process vs. thread

Process/thread states and APIs

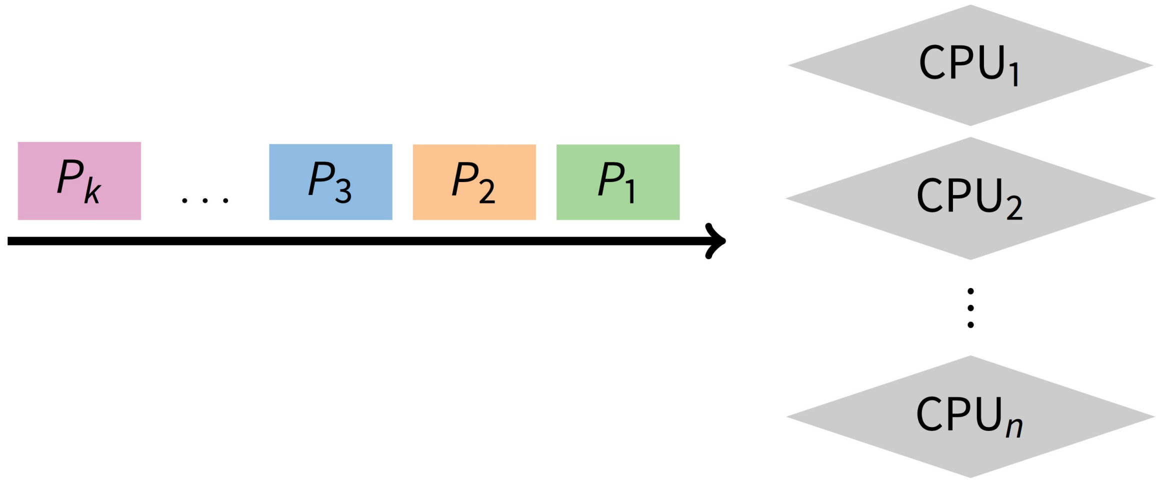
- state graph and queues
- process creation, deletion, waiting



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)**

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? → good schedule

- 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)

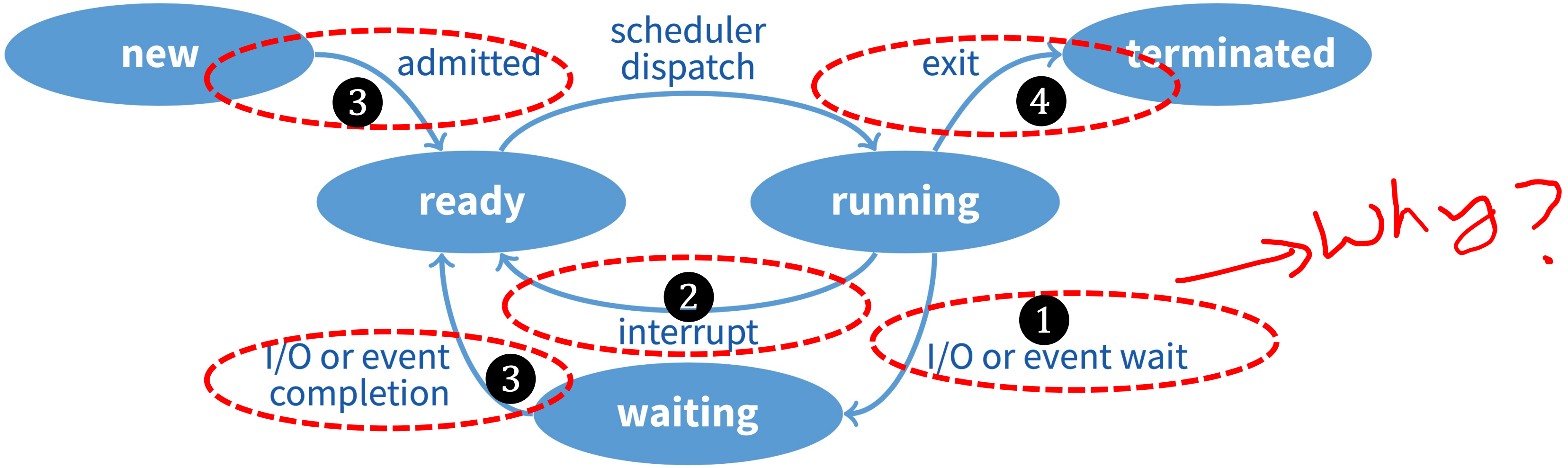
Interactive systems

- 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

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 Overview

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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

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

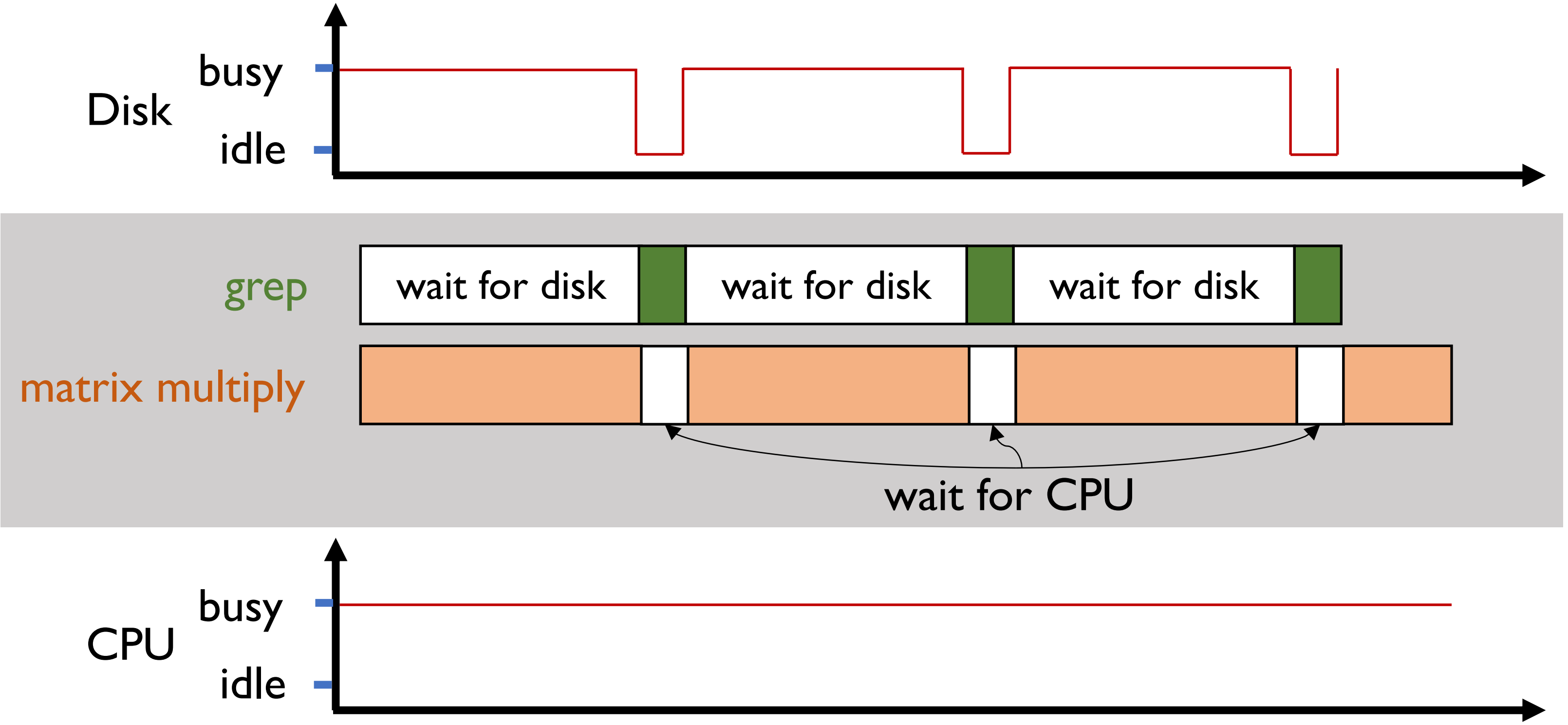
Scheduling 1-CPU system with n I/O devices like scheduling asymmetric $(n+1)$-CPU multiprocessor

- 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



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*

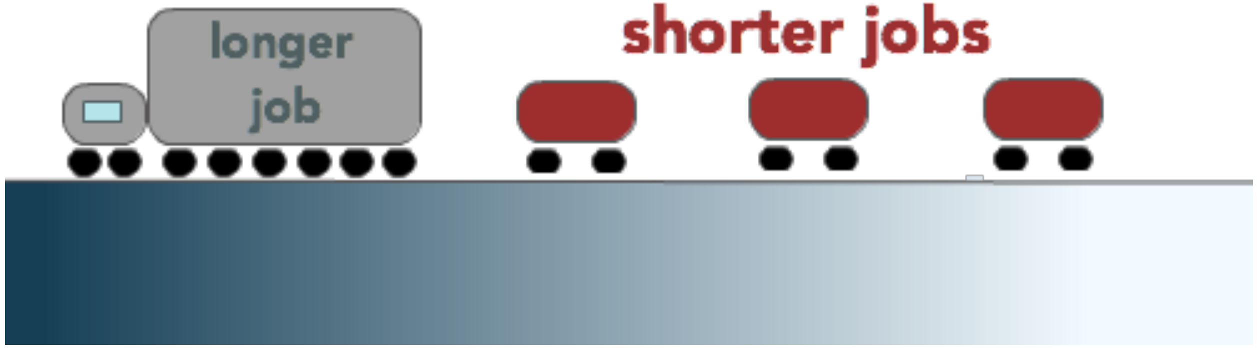


image source: http://web.cs.ucla.edu/classes/fall14/cs111/scribe/7a/convoy_effect.png

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

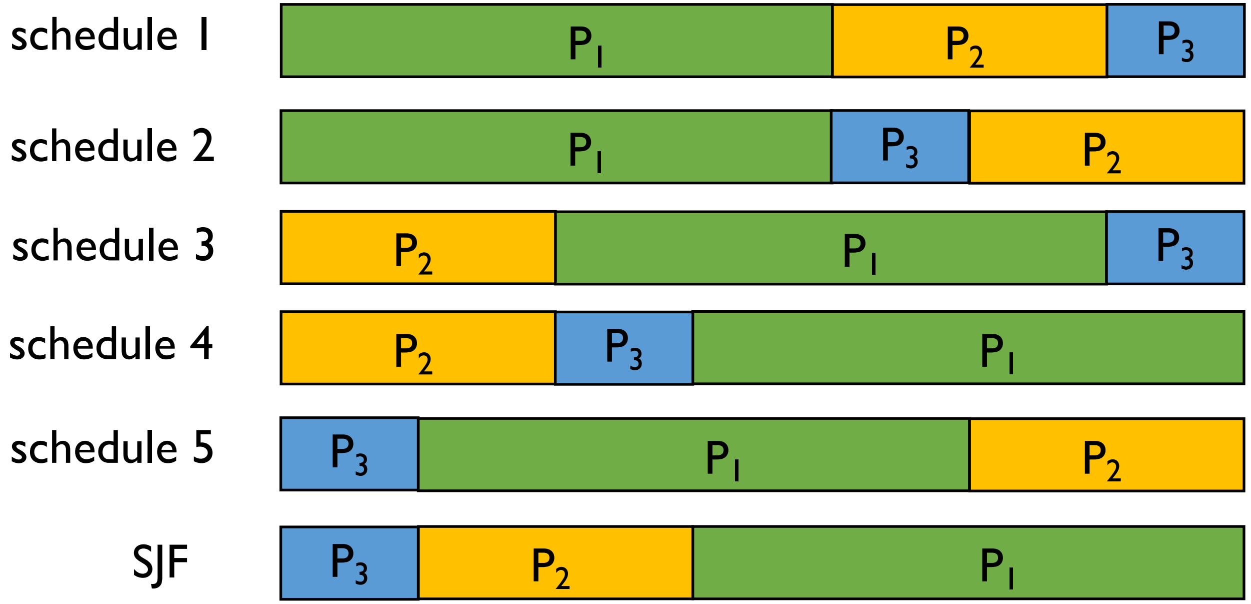
Average Waiting Time: (0 + 2 + 6) / 3 = 2.67

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? $= 3! = 6$



AWT = (0+8+12)/3 = 6.67

AWT = (0+8+10)/3 = 6

AWT = (0+4+12)/3 = 5.33

AWT = (0+4+6)/3 = 3.33

AWT = (0+2+10)/3 = 4

AWT = (0+2+6)/3 = 2.67

Shortest Job First (SJF)

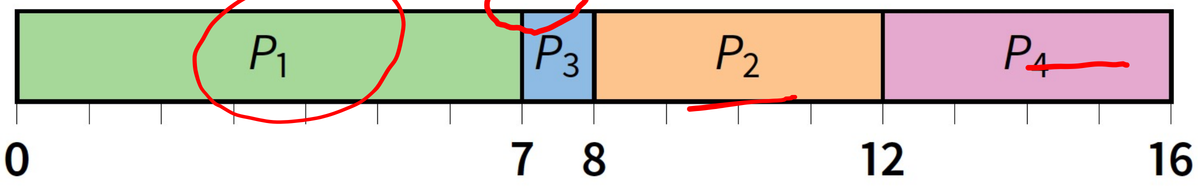
Two schemes

- 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

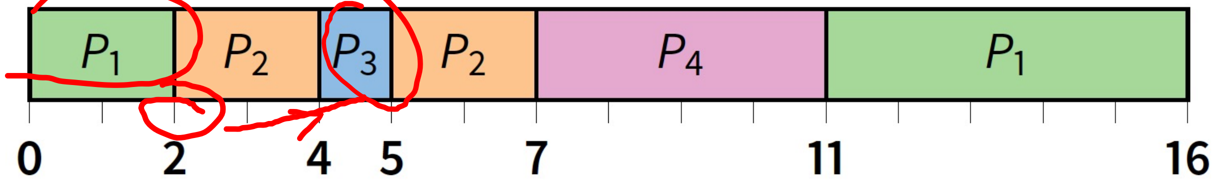
Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4

Non-preemptive



Preemptive

5



What is the AWT?

SJF Limitations

why?

Can potentially lead to unfairness or starvation

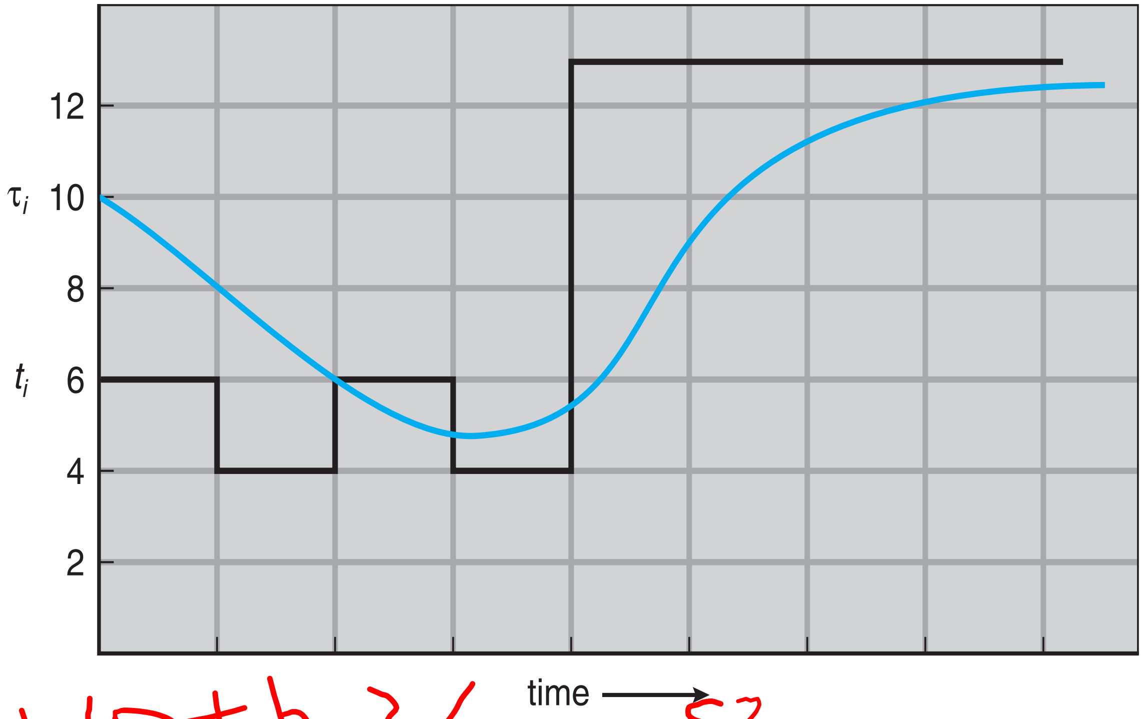
Impossible to know size of CPU burst ahead of time

- 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



$(10+6)/2 = 8$

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

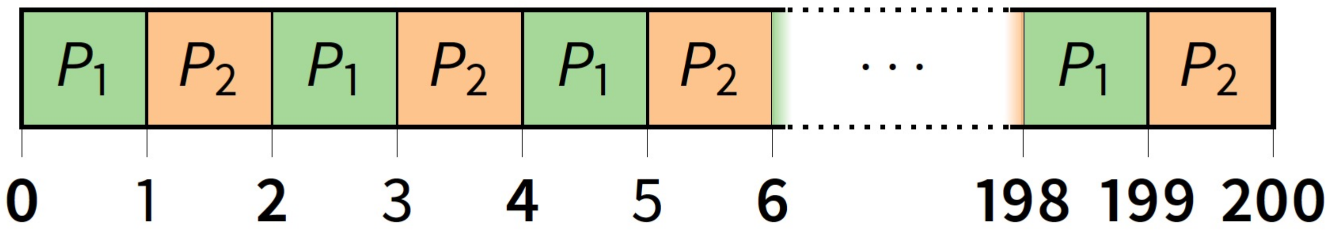
Disadvantages?

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:



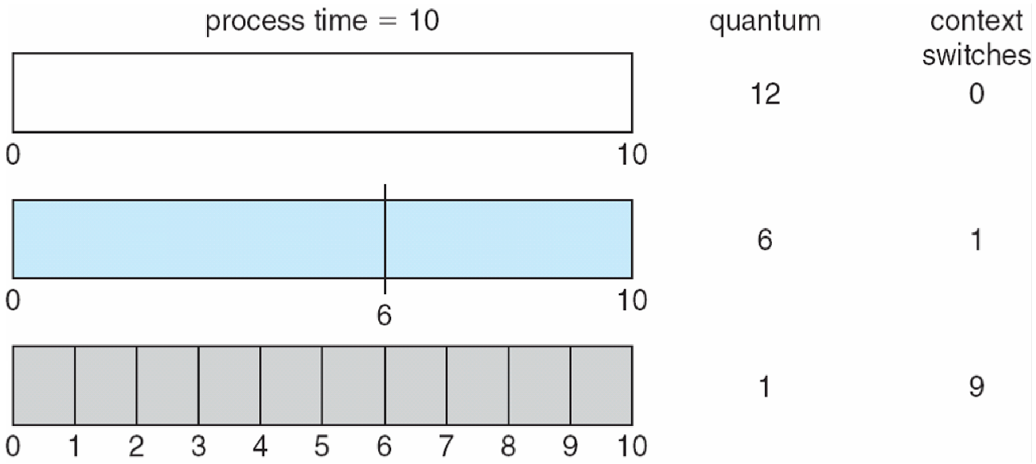
$$= \frac{199 + 200}{2} = 199.5$$

Even if context switches were free...

- What would average turnaround time be with RR?
- How does that compare to FCFS?

$$\frac{100 + 200}{2} = 150$$

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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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

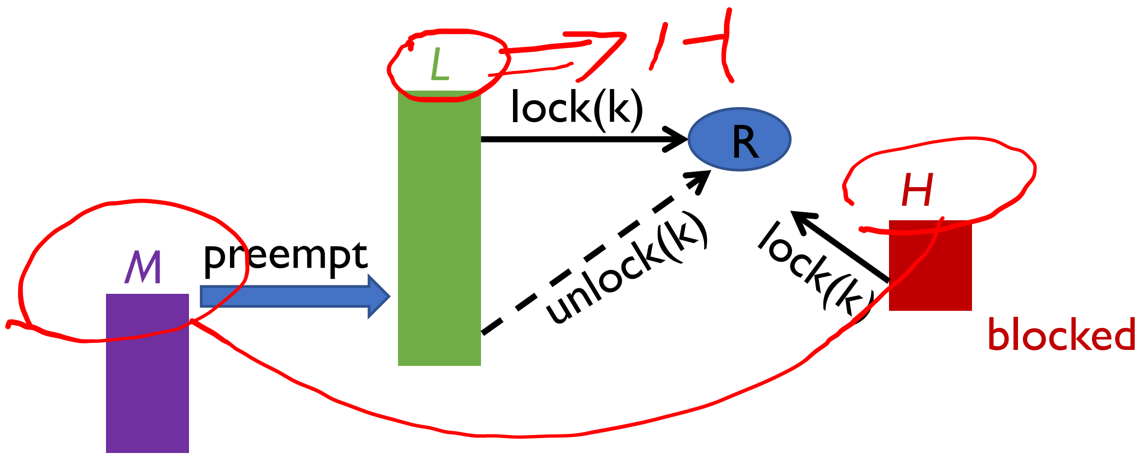
- Increase priority as a function of waiting time
- Decrease priority as a function of CPU consumption

Priority Inversion (1)

Caveat using Priority Scheduling w/ Synch Primitives

- Priority scheduling Rule
  1) Always pick highest-priority thread
  2) …*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



Priority Inversion (2)

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 <u>for the duration of its use of the shared resource</u>

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 k_2
- M waits on k, L's priority now $L_1 = 4$ (as before)
- Then H waits on 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

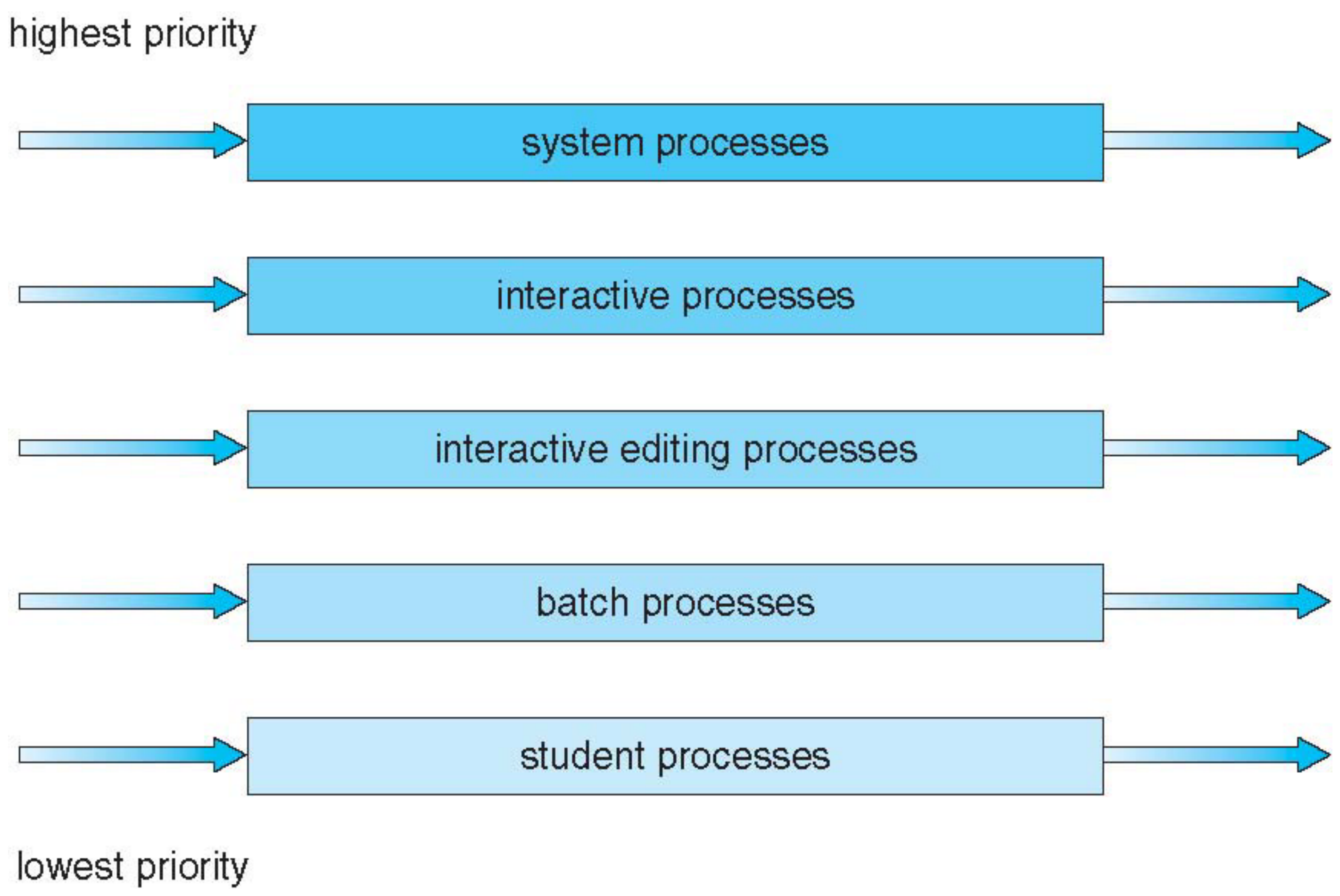
Combining scheduling algorithms to optimize for multiple objectives

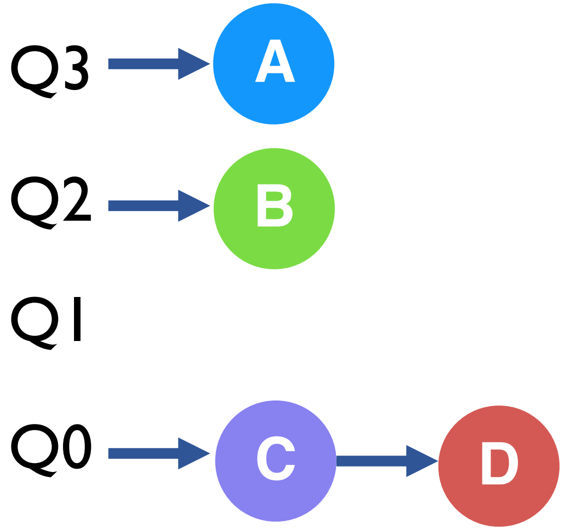
- Have multiple queues
- Use a different algorithm for each queue
- Move processes among queues

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)?

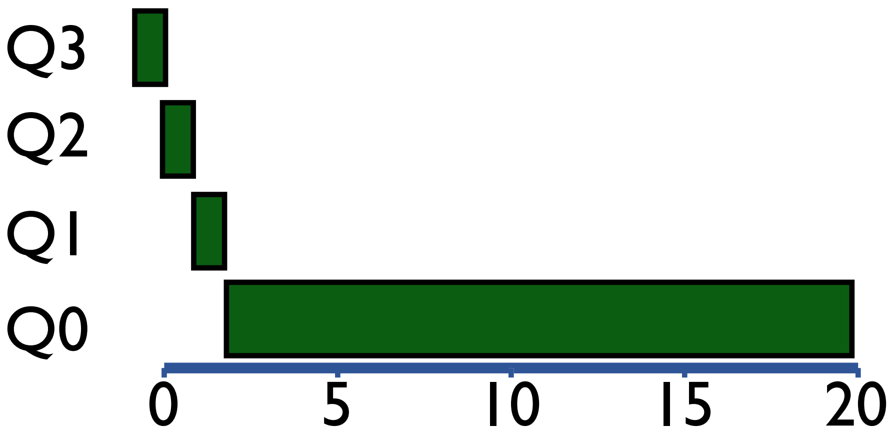
Idea:

- 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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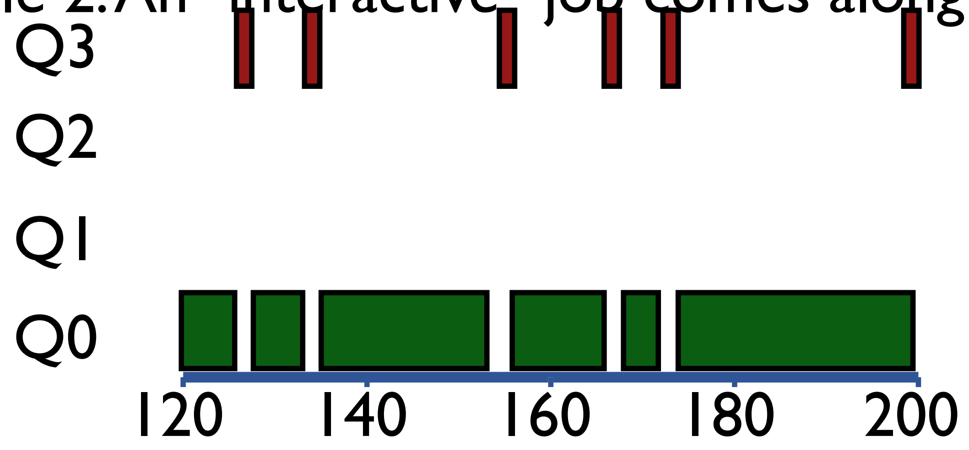

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- *Rule A:* Processes start at top priority
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- Example 1: A long-running "batch" job
- Example 2: An "interactive" job comes along
- **Problems:**
  - unforgiving + starvation
  - gaming the system
    - 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
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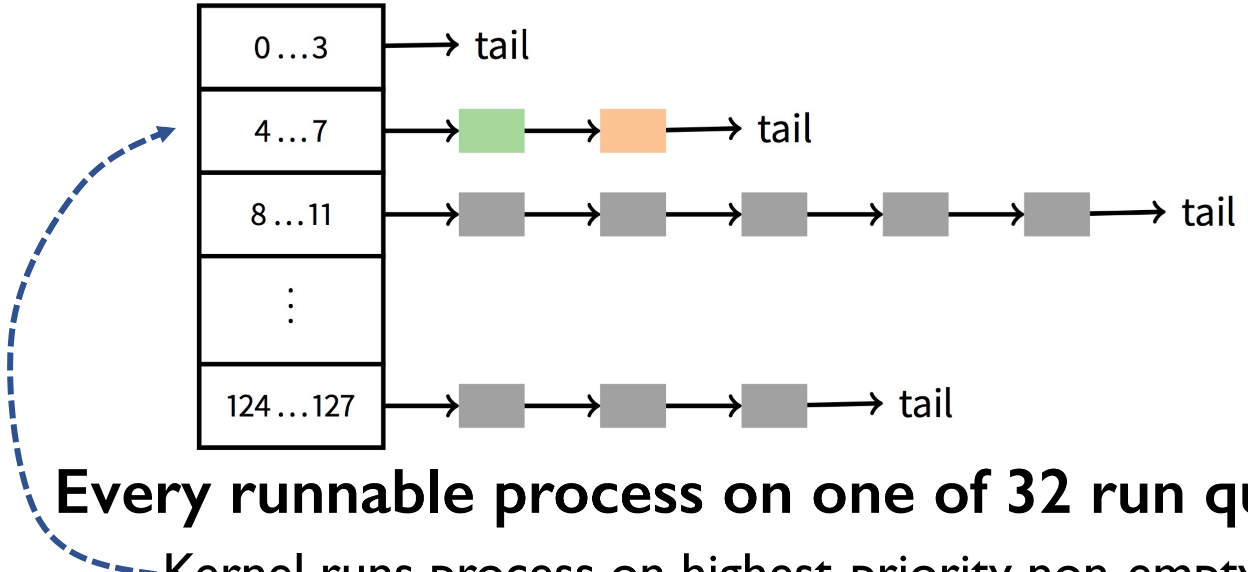
- Example 1: A long-running "batch" job
- Example 2: An "interactive" job comes along
- **Problems:**
  - unforgiving + starvation
  - gaming the system

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

- $$p\_usrpri \leftarrow 50 + \left(\frac{p\_estcpu}{4}\right) + 2 * p\_nice$$
- Calculated every 4 ticks, values are bounded to [50, 127]

Rationale: *decrease* priority linearly based on recent CPU

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

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4. ~~Advanced scheduling topics~~

Multiprocessor Scheduling Issues

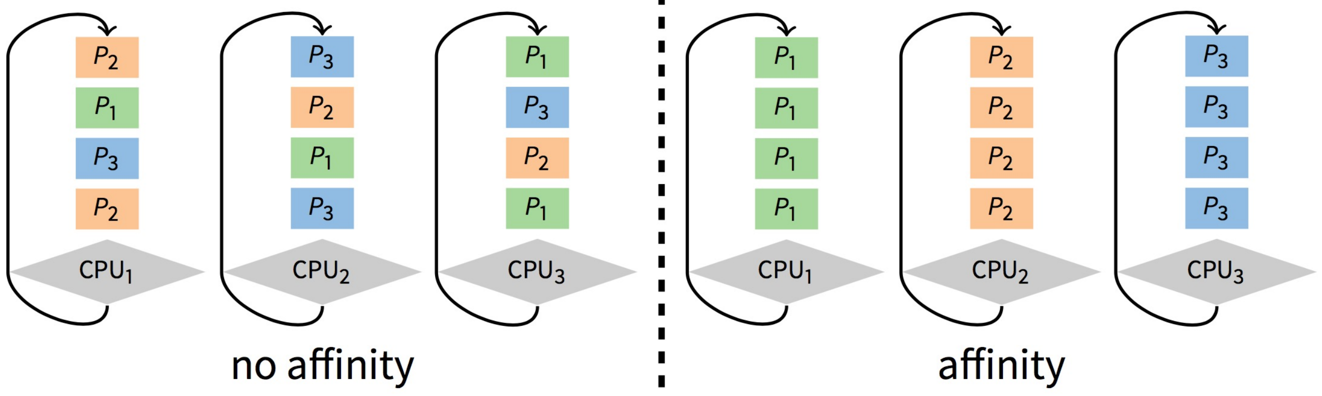
Must decide on more than which processes to run

- 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

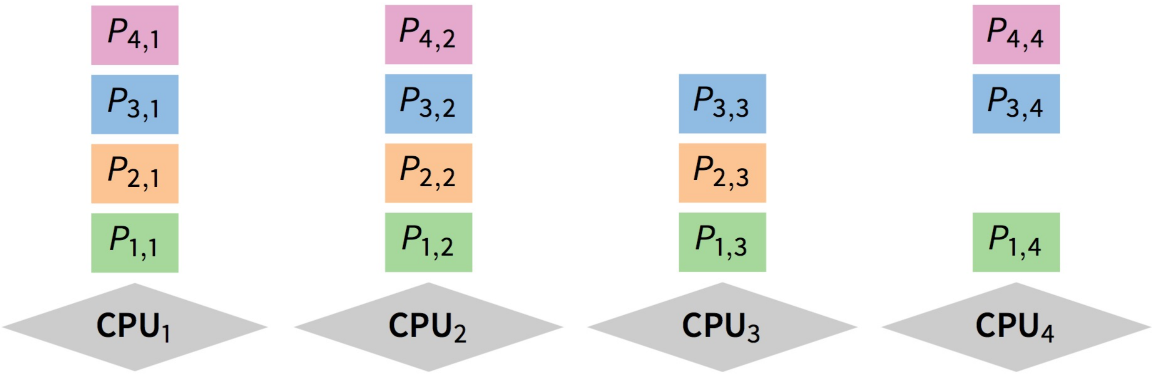
Multiprocessor Scheduling (cont)

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