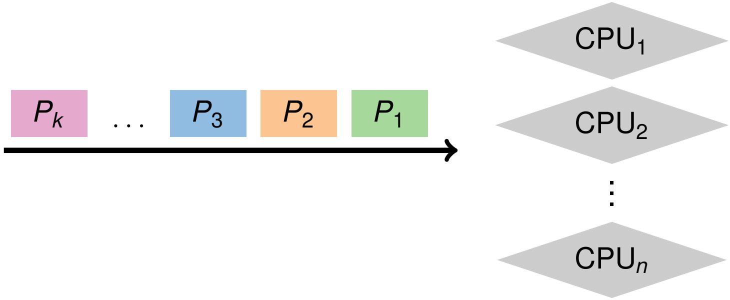
CPU scheduling

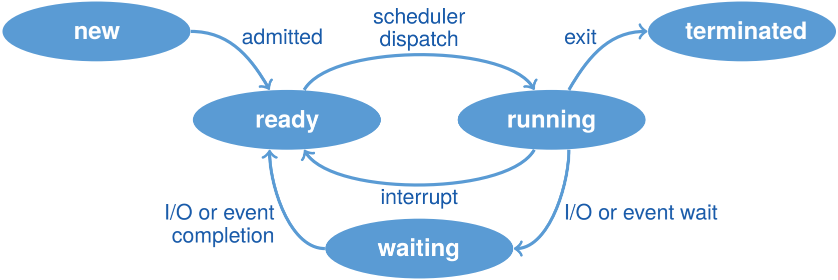


- The scheduling problem:
  - Have k jobs ready to run
  - Have $n \geq 1$ CPUs that can run them
- Which jobs should we assign to which CPU(s)?

Outline

1. Textbook scheduling
2. Priority scheduling

When do we schedule CPU?



- 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 new/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 processes that complete per unit time
  - Higher is better
- *Turnaround time* – time for each process to complete
  - Lower is better
- *Response time* – time from request to first response
  - I.e., time between **waiting**$\rightarrow$**ready** transition and **ready**$\rightarrow$**running** (e.g., key press to echo, not launch to exit)
  - Lower is better
- Above criteria are affected by secondary criteria
  - *CPU utilization* – fraction of time CPU doing productive work
  - *Waiting time* – time each process waits in ready queue

Example: FCFS Scheduling

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

- 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?

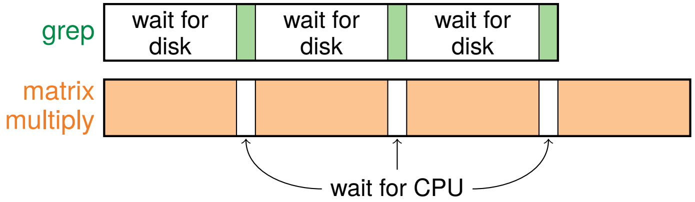
FCFS continued

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

- 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?

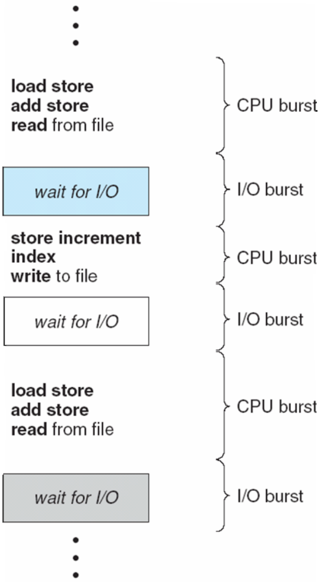
View CPU and I/O devices the same

- 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 $\Longrightarrow$ n+1 fold speedup!
- Example: disk-bound grep + CPU-bound matrix multiply
  - Overlap them just right? throughput will be almost doubled

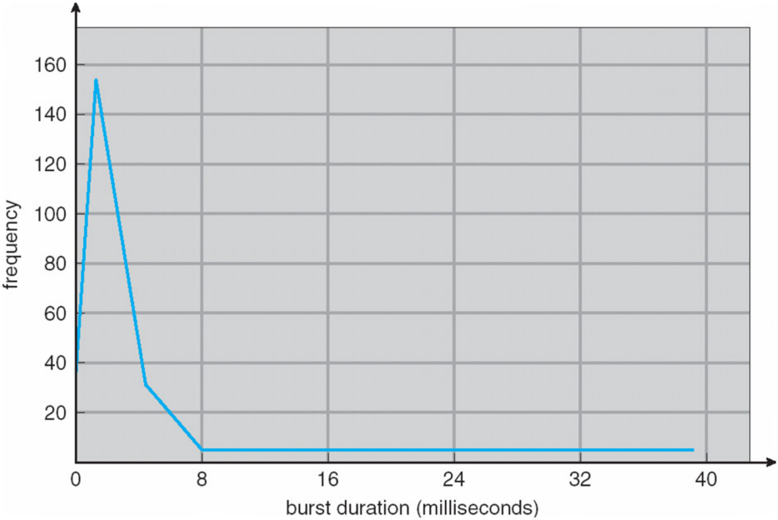


Bursts of computation & I/O

- 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 job runs (I/O devices idle)
  - CPU-bound job blocks
  - I/O-bound job(s) run, quickly block on I/O
  - CPU-bound job 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
  - Misnomer unless "job" = one CPU burst with no I/O
- 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 (Known as the *Shortest-Remaining-Time-First* or SRTF)
- What does SJF optimize?

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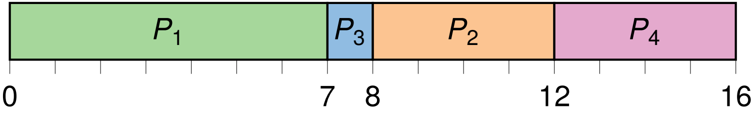
- What does SJF optimize?
  - Gives minimum average *waiting time* for a given set of processes

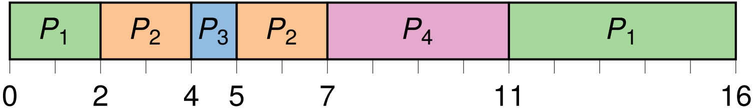
Examples

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

- Non-preemptive



- Preemptive



- Drawbacks?

SJF limitations

- Doesn't always minimize average TT
  - Only minimizes waiting 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 process's n^{th} CPU burst
  - τ_{n+1} estimated length of proc's $(n+1)^{\text{st}}$
  - Choose parameter α where $0 < \alpha \leq 1$
  - Let $\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n$

SJF limitations

- Doesn't always minimize average TT
  - Only minimizes waiting time
  - Example where turnaround time might be suboptimal?
  - Overall longer job has shorter bursts
- Can lead to unfairness or starvation
- In practice, can't actually predict the future
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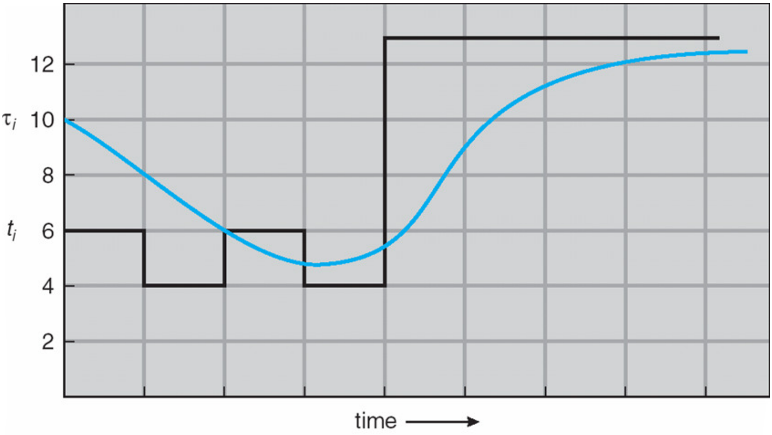
Exp. weighted average example



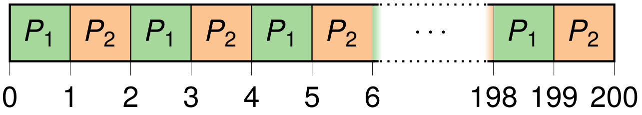
CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

Round robin (RR) 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 . . . 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?

RR disadvantages

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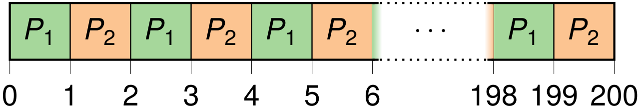

- Even if context switches were free. . .
  - What would average turnaround time be with RR? *199.5*
  - How does that compare to FCFS? *150*

Context switch costs

- What is the cost of a context switch?

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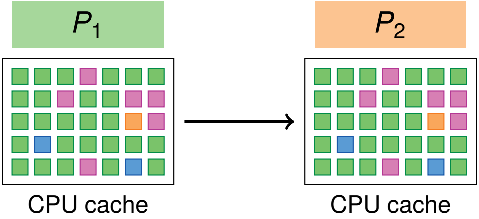
- Brute CPU time cost in kernel
  - Save and restore resisters, etc.
  - Switch address spaces (expensive instructions)
- Indirect costs: cache, buffer cache, & TLB misses



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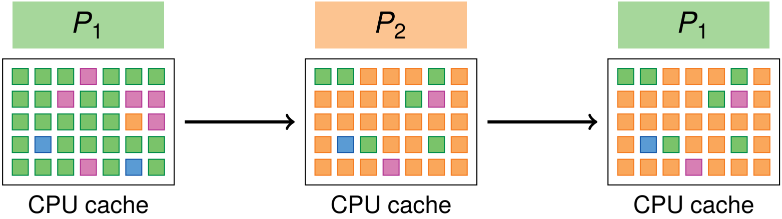
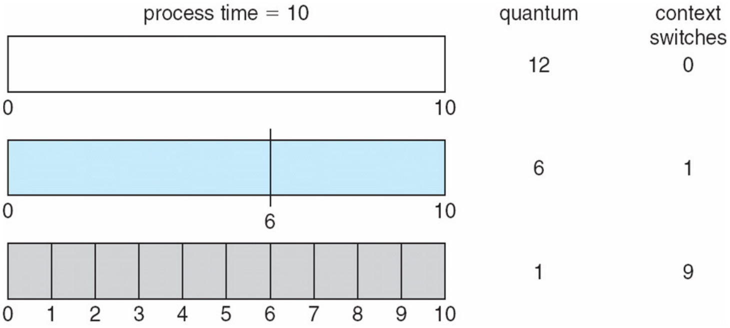
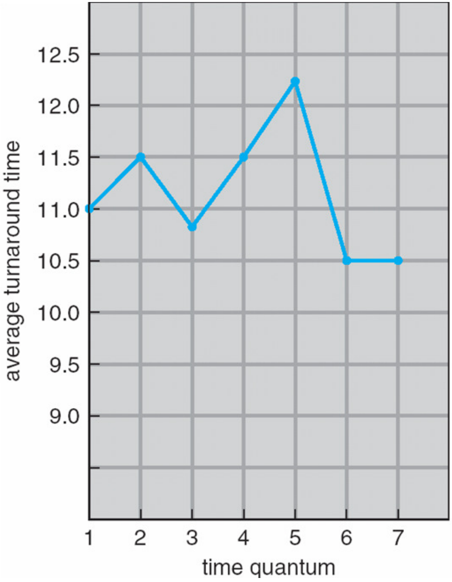


Time quantum



- 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

Turnaround time vs. quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

Two-level scheduling

- Switching to swapped out process very expensive
  - Swapped out process has most memory pages on disk
  - Will have to fault them all in while running
  - One disk access costs $\sim$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 scheduling CPU
  - Swapping in process is cost of memory "context switch"
  - So want "memory quantum" much larger than swapping cost

Outline

1. Textbook scheduling
2. Priority scheduling

Priority scheduling

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

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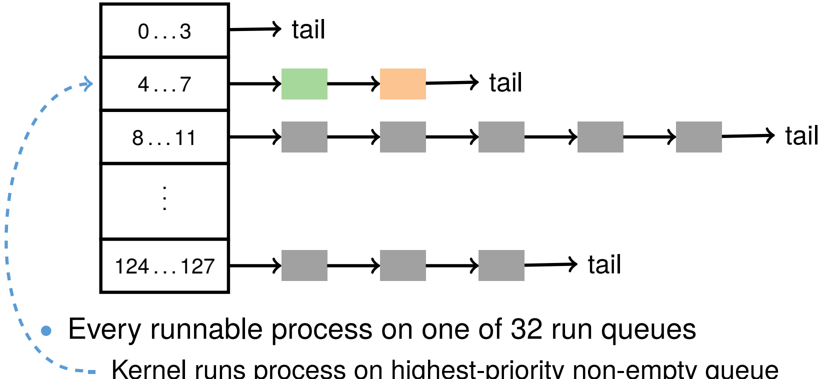
- Solution?
  - Aging: increase a process's priority as it waits

Multilevel feeedback 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

Process priority

- p_nice – user-settable weighting factor
- p_estcpu – per-process estimated CPU usage
  - Incremented whenever timer interrupt found process running
  - Decayed every second while process runnable

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

  - Load is sampled average of length of run queue plus short-term sleep queue over last minute
- Run queue determined by $\texttt{p\_usrpri}/4$

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

(value clipped if over 127)

Sleeping process increases priority

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

$$\texttt{p\_estcpu} \leftarrow \left(\frac{2 \cdot \text{load}}{2 \cdot \text{load} + 1}\right)^{\texttt{p\_slptime}} \times \texttt{p\_estcpu}$$

  - Approximates decay ignoring nice and past loads
- Previous description based on [McKusick] (*The Design and Implementation of the 4.4BSD Operating System*)

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

- Assume *H* at high priority, *L* at low priority
  - *L* acquires lock *l*.
  - Scenario 1: *H* tries to acquire *l*, fails, spins. *L* never gets to run.
  - Scenario 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
  - A thread's importance should increase with the importance of those that depend on it
  - Naïve priority schemes violate this

Priority donation

- Assume 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 $L_1 = \max(M, L) = 4$
  - Then H waits on l, L's priority raised to $\max(H, L_1) = 8$
- Example 2: Same L, M, H as above
  - L holds lock l, M holds lock l_2
  - M waits on l, L's priority now $L_1 = 4$ (as before)
  - Then H waits on l_2. M's priority goes to $M_1 = \max(H, M) = 8$, *and* L's priority raised to $\max(M_1, L_1) = 8$
- 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 $\max(L, M_1, \ldots, M_{1000}) = 4$.