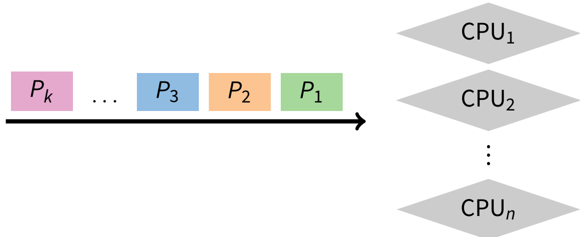
CPU scheduling

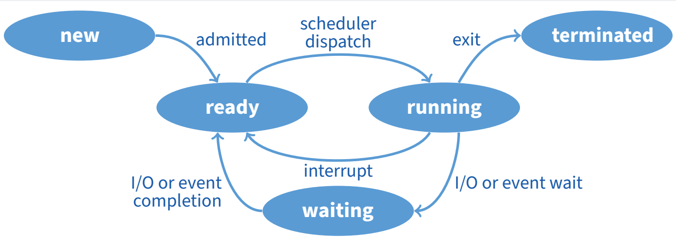


- **The scheduling problem:**
  - Have k jobs ready to run
  - Have $n \geq 1$ CPUs that can run them
- **Which jobs should we assign to which CPU(s)?**

Outline

1. Textbook scheduling
2. Priority scheduling
3. Advanced scheduling issues
4. Virtual time case studies

When do we schedule CPU?



- **Scheduling decisions may take place when a process:**
  1. Switches from running to ready state
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- **Preemptive schedulers run at all four points**

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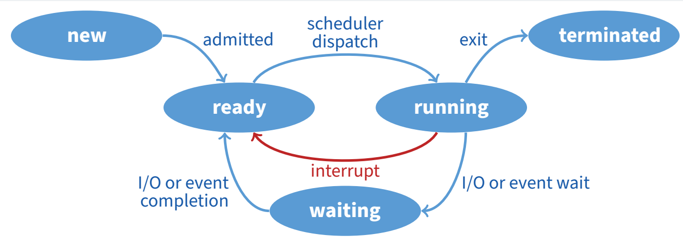

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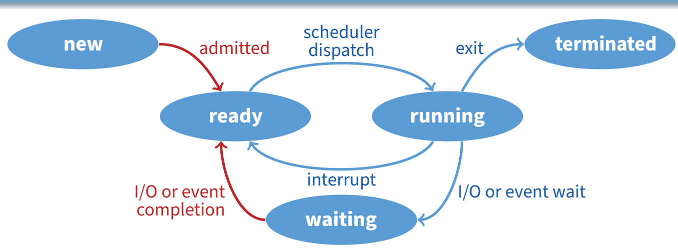

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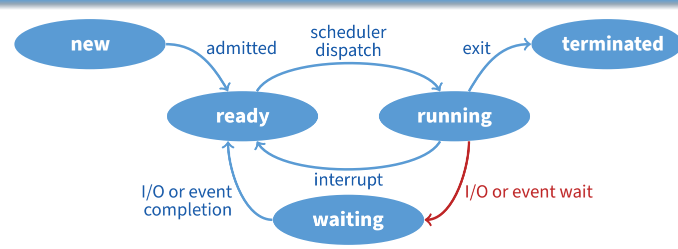

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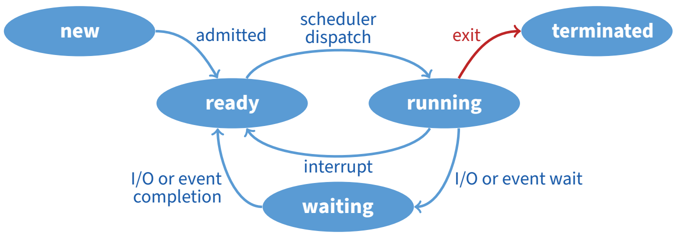

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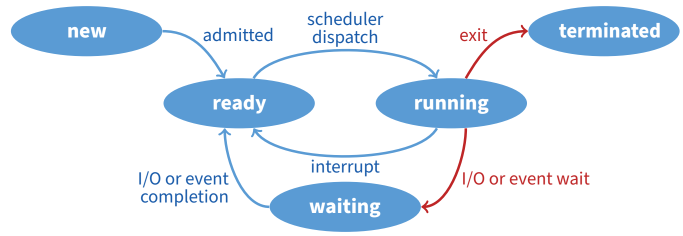

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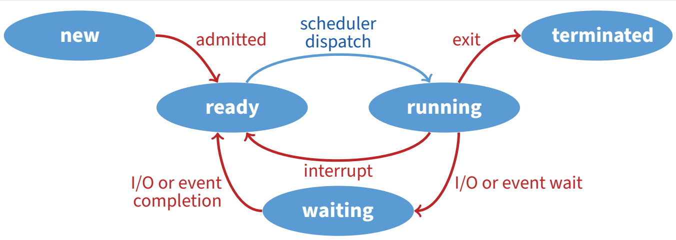

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Scheduling criteria

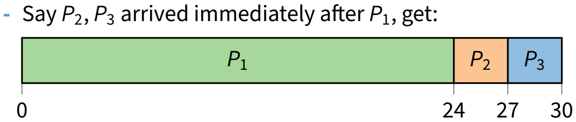
- **Why do we care?**
  - What goals should we have for a scheduling algorithm?

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**→**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* – fraction of time CPU doing productive work
  - *Waiting time* – time each process waits in ready queue

Example: FCFS Scheduling

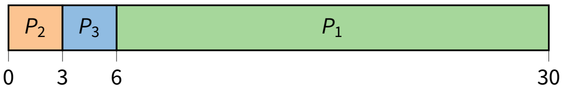
- **Run jobs in order that they arrive**
  - Called "*First-come first-served*" (FCFS)
  - E.g., Say P_1 needs 24 sec, while P_2 and P_3 need 3.
  - Say P_2, P_3 arrived immediately after P_1, get:



- **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
- **Can a scheduling algorithm improve throughput?**

FCFS continued

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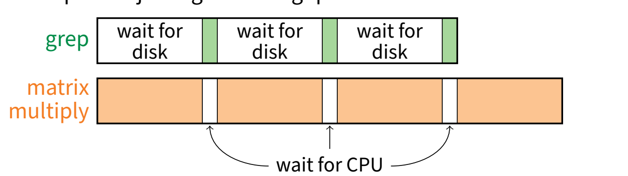
- **Lesson: scheduling algorithm can reduce TT**
  - Minimizing waiting time can improve RT and TT
- **Can a scheduling algorithm improve throughput?**
  - Yes, if jobs require both computation and I/O

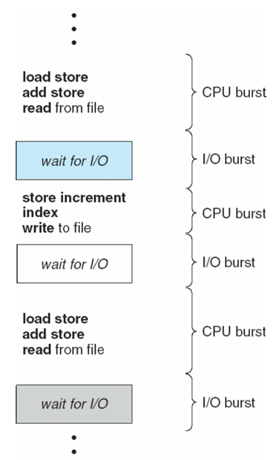
View CPU and I/O devices the same

- **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 throughput gain!
- **Example: disk-bound grep + CPU-bound matrix multiply**
  - Overlap them just right? throughput will be almost doubled

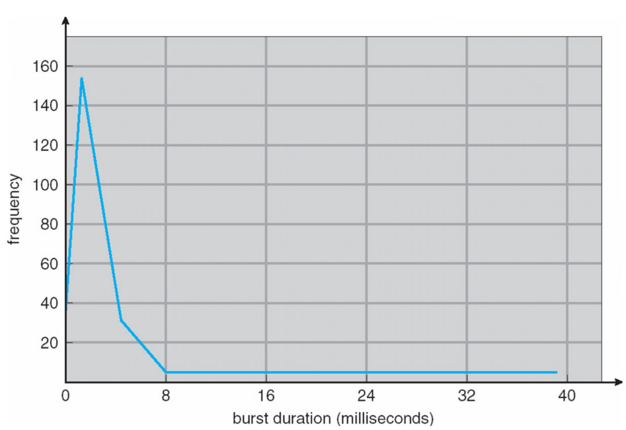


Bursts of computation & I/O

- **Jobs contain I/O and computation**
  - Bursts of computation
  - Then must wait for I/O
- **To maximize throughput, maximize both CPU and I/O device utilization**
- **How to do?**
  - Overlap computation from one job with I/O from other 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)
  - Eventually, CPU-bound job blocks
  - I/O-bound jobs run, but each quickly blocks on I/O
  - CPU-bound job unblocks, runs again
  - All I/O requests complete, but CPU-bound job still hogs CPU
  - I/O devices sit idle since I/O-bound jobs can't issue next requests
- **Simple hack: run process whose I/O completed**
  - What is a potential problem?

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- **Simple hack: run process whose I/O completed**
  - What is a potential problem?
    I/O-bound jobs can starve CPU-bound one

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
    [term coined for context where there is no I/O, only compute]
- **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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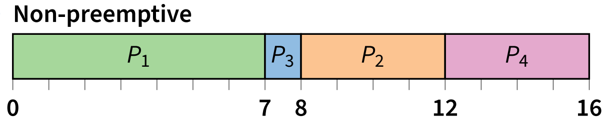
- **What does SJF optimize?**
  - Gives minimum average *waiting time* for a given set of processes

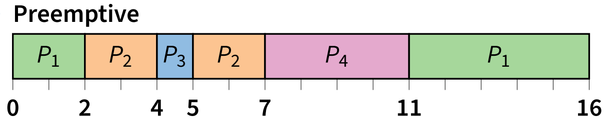
Examples

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**
- **But can estimate CPU burst length based on past**
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  - t_n actual length of process's n^{th} CPU burst
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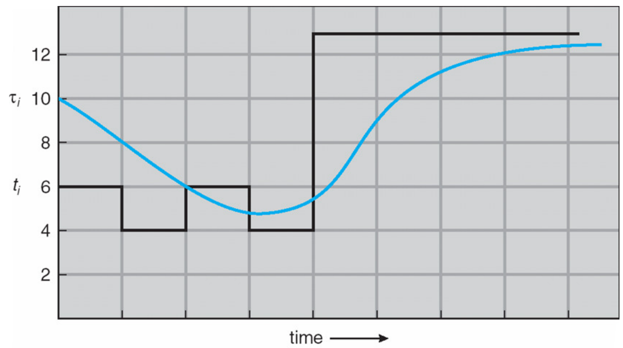
Exp. weighted average example



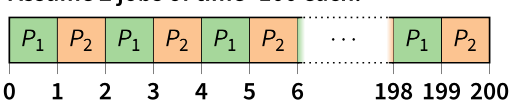
CPU burst (t_i)		6	4	6	4	13	13	13	...
"guess" (τ_i)	10	8	6	6	5	9	11	12	...

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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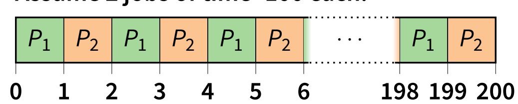

- **Even if context switches were free. . .**
  - What would average turnaround time be with RR? *199.5*
  - How does that compare to FCFS? *150*

Context switch costs

- **What is the cost of a context switch?**

Context switch costs

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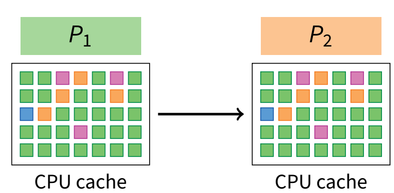
- **Brute CPU time cost in kernel**
  - Save and restore resisters, etc.
  - Switch address spaces (expensive instructions)
- **Indirect costs: cache, buffer cache, & TLB misses**



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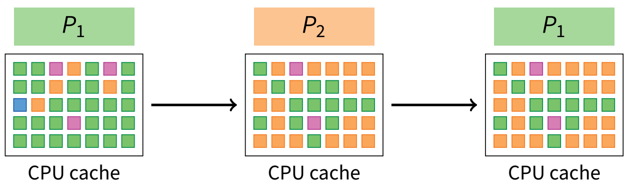
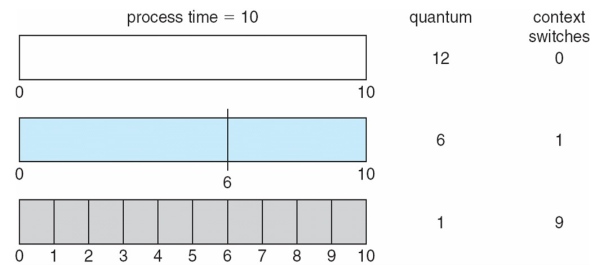
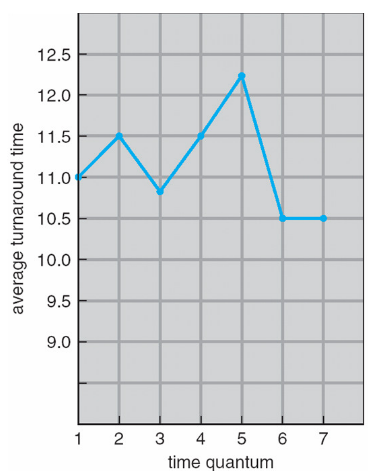


Time quantum



- **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

- **Under memory constraints, may need to *swap* process to disk**
- **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 ∼10ms. On 1GHz machine, 10ms = 10 million cycles!
- **Solution: 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

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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 priority scheduling where priority is the predicted next CPU burst time**
- **Starvation – low priority processes may never execute**
- **Solution?**

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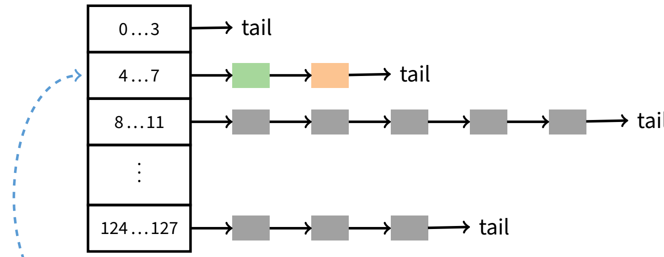
- **Solution?**
  - Aging: increase a process's priority as it waits

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** 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][1] (*The Design and Implementation of the 4.4BSD Operating System*)**

[1] 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:**

$$\texttt{priority} = 63 - \left(\frac{\texttt{recent\_cpu}}{4}\right) - 2 \cdot \texttt{nice}$$

Thread scheduling

- **With thread library, have two scheduling decisions:**
  - *Local Scheduling* – User-level thread library decides which user (green) thread to put onto an available native (i.e., kernel) thread
  - *Global Scheduling* – Kernel decides which native 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 native 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.
  - Scenario 1 (ℓ a spinlock): H tries to acquire ℓ, fails, spins. L never gets to run.
  - Scenario 2 (ℓ a mutex): H tries to acquire ℓ, fails, blocks. M enters system at medium priority. L never gets to run.
  - Both scenarios 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

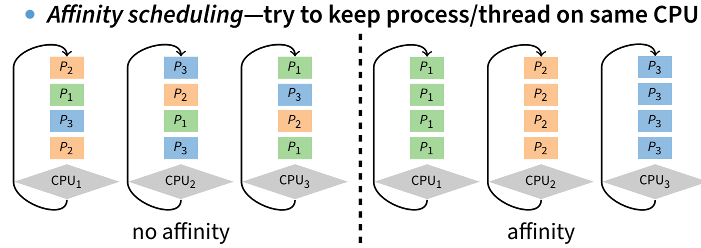
Priority donation

- **Say higher number = higher priority (like Pintos)**
- **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_1, M holds lock ℓ_2
  - M waits on ℓ_1, 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 $\max(L, M_1, \ldots, M_{1000}) = 4$.

Outline

Multiprocessor scheduling issues

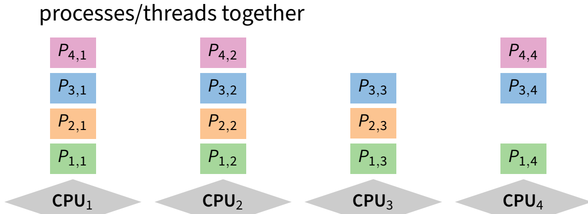
- **Must decide on more than which processes to run**
  - Must decide on which CPU to run which process
- **Moving between CPUs has costs**
  - More cache misses, depending on arch. more TLB misses too
- ***Affinity scheduling*—try to keep process/thread on same CPU**



  - But also prevent load imbalances
  - Do *cost-benefit* analysis when deciding to migrate… affinity can also be harmful, 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 audio playback 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 $\sum \frac{\text{CPU}}{\text{period}} \leq 1$ (not counting switch time)
- **Variety of scheduling strategies**
  - E.g., first deadline first (works if schedulable, otherwise fails spectacularly)

Outline

1. Textbook scheduling
2. Priority scheduling
3. Advanced scheduling issues
4. Virtual time case studies

Scheduling with virtual time

- **Many modern schedulers employ notion of *virtual time***
  - Idea: Equalize virtual CPU time consumed by different processes
  - Higher-priority processes consume virtual time more slowly
- **Forms the basis of the current linux scheduler, CFS**
- **Case study: Borrowed Virtual Time (BVT) [Duda]**
- **BVT runs process with lowest *effective virtual time***
  - A_i – *actual virtual time* consumed by process i
  - *effective virtual time* $E_i = A_i - (\text{warp}_i \ ? \ W_i : 0)$
  - Special warp factor allows borrowing against future CPU time …hence name of algorithm

Process weights

- **Each process *i*'s faction of CPU determined by weight w_i**
  - i should get $w_i / \sum_j w_j$ faction of CPU
  - So w_i is real seconds per virtual second that process i has CPU
- **When i consumes t CPU time, track it: A_i += t/w_i**
- **Example: gcc (weight 2), bigsim (weight 1)**
  - Assuming no IO, runs: gcc, gcc, bigsim, gcc, gcc, bigsim, …
  - Lots of context switches, not so good for performance
- **Add in context switch allowance, C**
  - Only switch from i to j if $E_j \leq E_i - C/w_i$
  - C is wall-clock time ($\gg$ context switch cost), so must divide by w_i
  - Ignore C if j just became runable…why?

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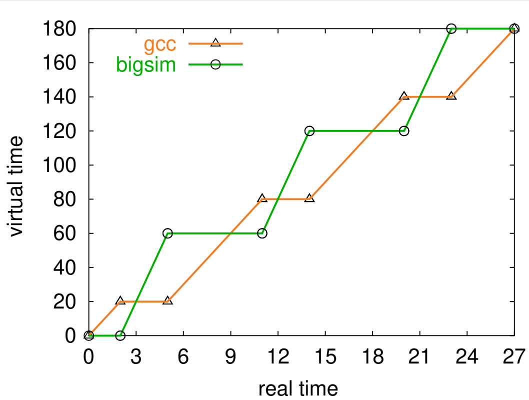
  - C is wall-clock time ($\gg$ context switch cost), so must divide by w_i
  - Ignore C if j just became runable to avoid affecting response time

BVT example

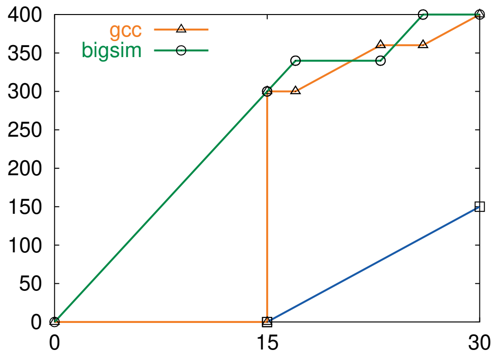


- **gcc has weight 2, bigsim weight 1, $C = 2$, no I/O**
  - bigsim consumes virtual time at twice the rate of gcc
  - Processes run for C time after lines cross before context switch

Sleep/wakeup

- **Must lower priority (increase A_i) after wakeup**
  - Otherwise process with very low A_i would starve everyone
- **Bound lag with Scheduler Virtual Time (SVT)**
  - SVT is minimum A_j for all runnable threads j
  - When waking i from voluntary sleep, set $A_i \leftarrow \max(A_i, SVT)$
- **Note voluntary/involuntary sleep distinction**
  - E.g., Don't reset A_j to SVT after page fault
  - Faulting thread needs a chance to catch up
  - But do set $A_i \leftarrow \max(A_i, SVT)$ after socket read
- **Note: Even with SVT A_i can never decrease**
  - After short sleep, might have $A_i >$ SVT, so $\max(A_i, SVT) = A_i$
  - i never gets more than its fair share of CPU in long run

gcc wakes up after I/O

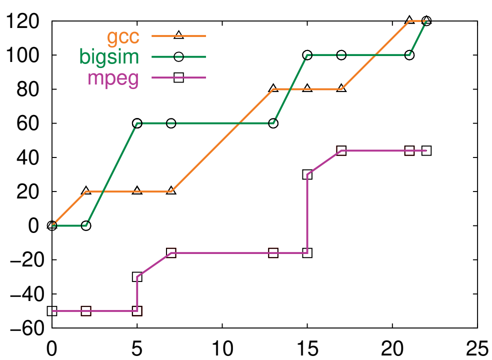


- **gcc's A_i gets reset to SVT on wakeup**
  - Otherwise, would be at lower (blue) line and starve bigsim

Real-time threads

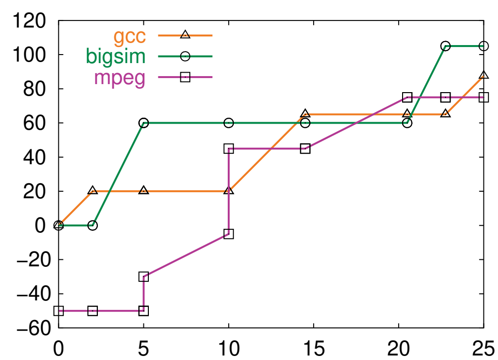
- **Also want to support time-critical tasks**
  - E.g., mpeg player must run every 10 clock ticks
- **Recall** $E_i = A_i - (\textbf{warp}_i \ ? \ W_i : 0)$
  - W_i is *warp factor* – gives thread precedence
  - Just give mpeg player *i* large W_i factor
  - Will get CPU whenever it is runable
  - But long term CPU share won't exceed $w_i / \sum_j w_j$
- **Note W_i only matters when warp$_i$ is true**
  - Can set warp$_i$ with a syscall, or have it set in signal handler
  - Also gets cleared if *i* keeps using CPU for L_i time
  - L_i limit gets reset every U_i time
  - $L_i = 0$ means no limit – okay for small W_i value

Running warped



- **mpeg player runs with -50 warp value**
  - Always gets CPU when needed, never misses a frame

Warped thread hogging CPU



- **mpeg goes into tight loop at time 5**
- **Exceeds L_i at time 10, so warp$_i \leftarrow$ false**

BVT example: Search engine

- **Common queries 150 times faster than uncommon**
  - Have 10-thread pool of threads to handle requests
  - Assign W_i value sufficient to process fast query (say 50)
- **Say 1 slow query, small trickle of fast queries**
  - Fast queries come in, warped by 50, execute immediately
  - Slow query runs in background
  - Good for turnaround time
- **Say 1 slow query, but many fast queries**
  - At first, only fast queries run
  - But SVT is bounded by A_i of slow query thread *i*
  - Recall fast query thread *j* gets $A_j = max(A_j, SVT) = A_j$; eventually $SVT < A_j$ and a bit later $A_j - W_j > A_i$.
  - At that point thread *i* will run again, so no starvation

Case study: SMART

- **Key idea: Separate *importance* from *urgency***
  - Figure out which processes are important enough to run
  - Run whichever of these is most urgent
- **Importance = $\langle priority, BVFT \rangle$ value tuple**
  - *priority* – parameter set by user or administrator (higher is better)
    - Takes absolute priority over BVFT
  - *BVFT* – Biased Virtual Finishing Time (lower is better)
    - virtual time consumed + virtual length of next CPU burst
    - I.e., virtual time at which quantum would end if process scheduled now
    - Bias is like negative warp, see paper for details
- **Urgency = next deadline (sooner is more urgent)**

SMART algorithm

- **If most important ready task (ready task with best value tuple) is conventional (not real-time), run it**
- **Consider all real-time tasks with better value tuples than the best ready conventional task**
- **For each such real-time task, starting from the best value-tuple**
  - Can you run it without missing deadlines of more important tasks?
  - If so, add to *schedulable* set
- **Run task with earliest deadline in schedulable set**
- **Send signal to tasks that won't meet their deadlines**