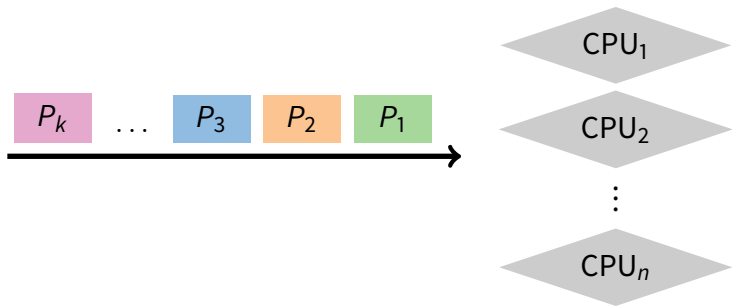


# CPU scheduling

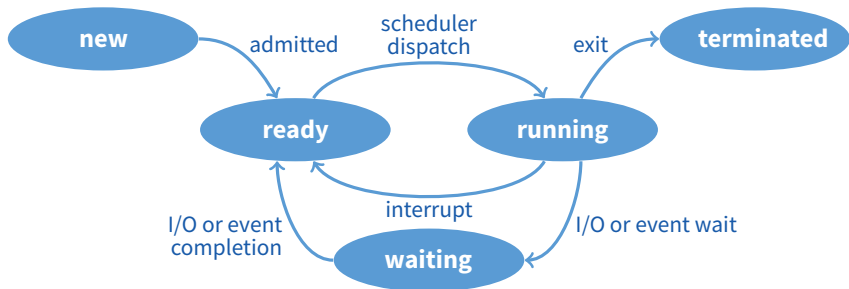


- **The scheduling problem:**
  - Have  $k$  jobs ready to run
  - Have  $n \geq 1$  CPUs that can run them
- **Which jobs should we assign to which CPU(s)?**

# Outline

- 1 Textbook scheduling
- 2 Priority scheduling
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- 4 Virtual time case studies

# 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**→**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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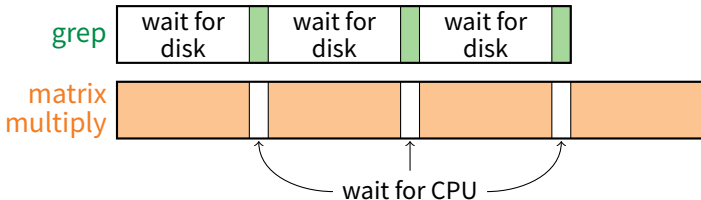


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  - Average TT:  $(30 + 3 + 6)/3 = 13$  – much less than 27
- Lesson: scheduling algorithm can reduce TT
  - Minimizing waiting time can improve RT and TT
- Can a scheduling algorithm improve throughput?
  - Yes, if jobs require both computation and I/O



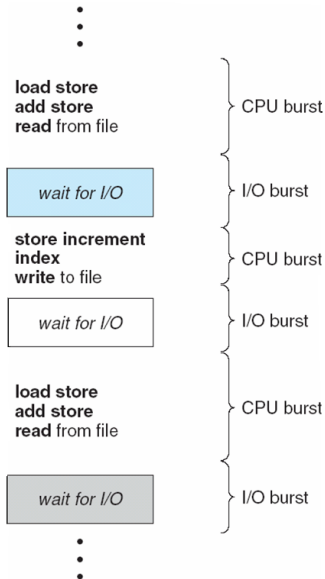
# View CPU and I/O devices the same

- **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  $\Rightarrow (n + 1)$ -fold throughput gain!
- **Example: disk-bound grep + CPU-bound matrix multiply**
  - Overlap them just right? throughput will be almost doubled

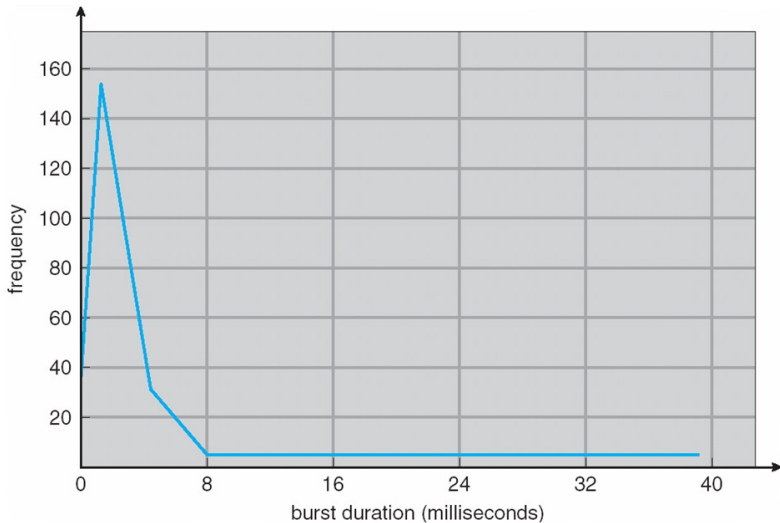


# Bursts of computation & I/O

- **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?

# FCFS Convoy effect

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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
- **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?**

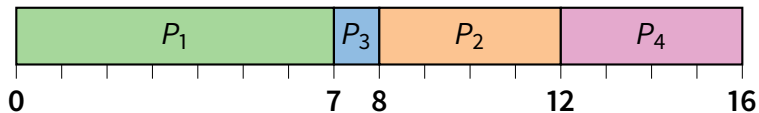
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- **What does SJF optimize?**
  - Gives minimum average *waiting time* for a given set of processes

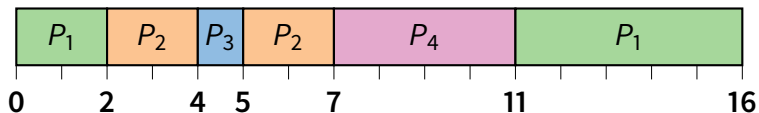
# Examples

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?



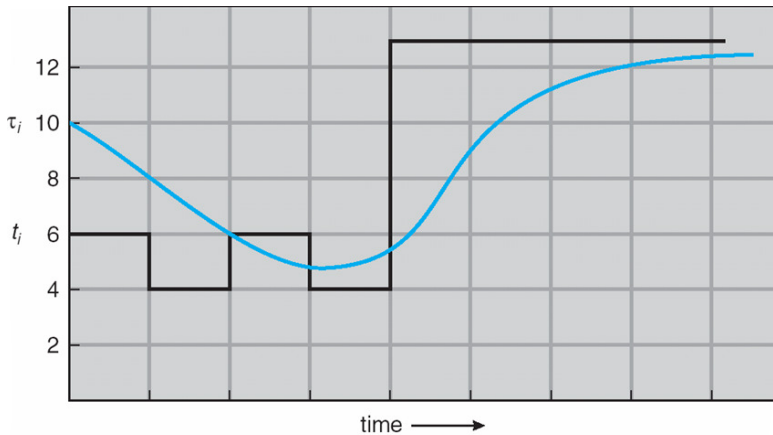
# SJF limitations

- **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  $n^{\text{th}}$  CPU burst
  - $\tau_{n+1}$  estimated length of proc's  $(n + 1)^{\text{st}}$
  - Choose parameter  $\alpha$  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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  - $t_n$  actual length of process's  $n^{\text{th}}$  CPU burst
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# Exp. weighted average example



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

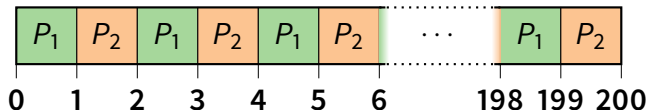
# Round robin (RR) scheduling



- **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

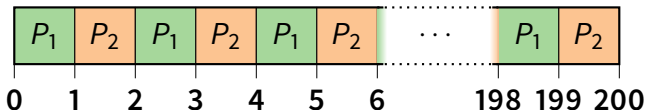
- Varying sized jobs are good ... what about same-sized jobs?
- Assume 2 jobs of time=100 each:



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

# RR disadvantages

- Varying sized jobs are good ... what about same-sized jobs?
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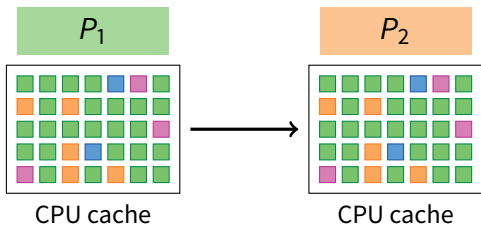
- Even if context switches were free...
  - What would average turnaround time be with RR? 199.5
  - How does that compare to FCFS? 150

# Context switch costs

- What is the cost of a context switch?

# Context switch costs

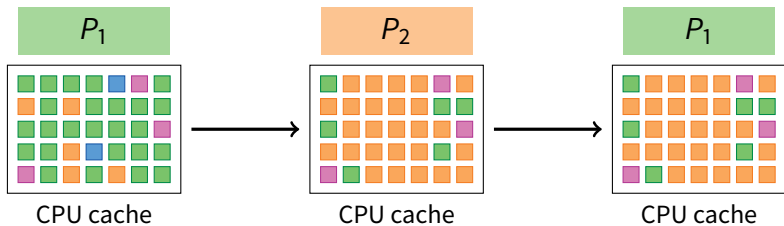
- What is the cost of a context switch?
- Brute CPU time cost in kernel
  - Save and restore registers, etc.
  - Switch address spaces (expensive instructions)
- Indirect costs: cache, buffer cache, & TLB misses



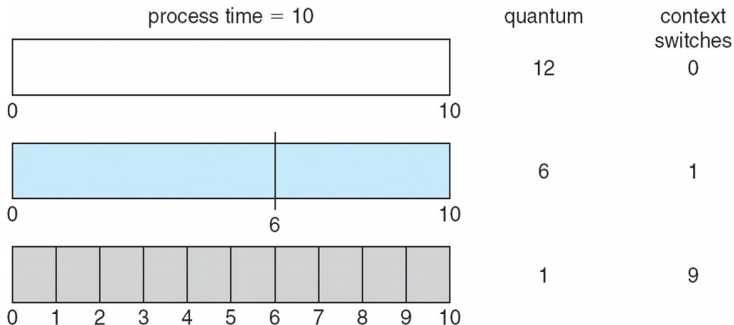


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# Time quantum

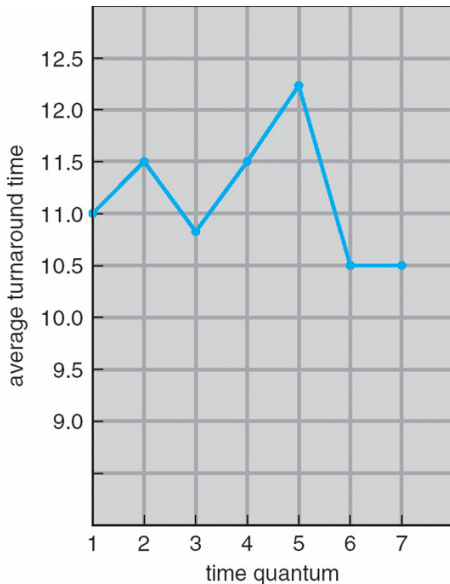


- **How to pick quantum?**

- 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  $\sim 10\text{ms}$ . On 1GHz machine,  $10\text{ms} = 10$  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

# Outline

- 1 Textbook scheduling
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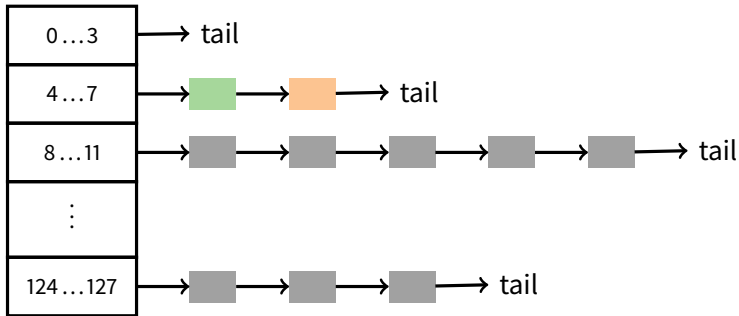
# Priority scheduling

- **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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- **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-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

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

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

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

(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**

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

- Approximates decay ignoring nice and past loads
- **Previous description based on [McKusick]<sup>1</sup> (*The Design and Implementation of the 4.4BSD Operating System*)**

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<sup>1</sup>See [library.stanford.edu](http://library.stanford.edu) for off-campus access

- **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:**

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

# 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  $\ell$ .
  - Scenario 1:  $H$  tries to acquire  $\ell$ , fails, spins.  $L$  never gets to run.
  - Scenario 2:  $H$  tries to acquire  $\ell$ , 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

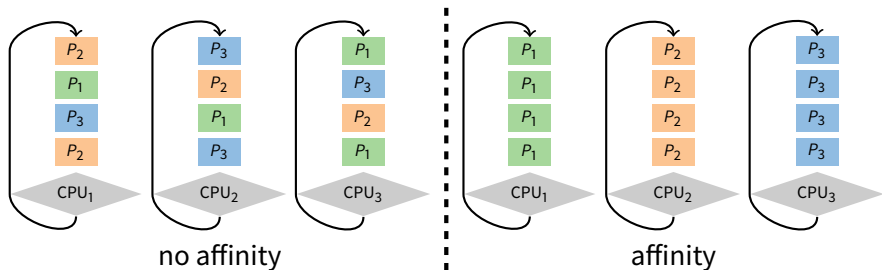
- Say higher number = higher priority (like Pintos)
- **Example 1:  $L$  (prio 2),  $M$  (prio 4),  $H$  (prio 8)**
  - $L$  holds lock  $\ell$
  - $M$  waits on  $\ell$ ,  $L$ 's priority raised to  $L_1 = \max(M, L) = 4$
  - Then  $H$  waits on  $\ell$ ,  $L$ 's priority raised to  $\max(H, L_1) = 8$
- **Example 2: Same  $L, M, H$  as above**
  - $L$  holds lock  $\ell$ ,  $M$  holds lock  $\ell_2$
  - $M$  waits on  $\ell$ ,  $L$ 's priority now  $L_1 = 4$  (as before)
  - Then  $H$  waits on  $\ell_2$ .  $M$ '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),  $M_1, \dots, M_{1000}$  (all prio 4)**
  - $L$  has  $\ell$ , and  $M_1, \dots, M_{1000}$  all block on  $\ell$ .  $L$ 's priority is  $\max(L, M_1, \dots, M_{1000}) = 4$ .

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# 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

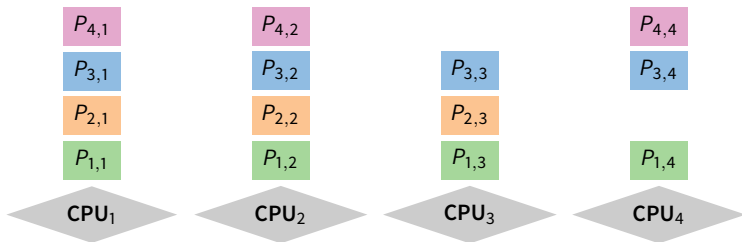


- But also prevent load imbalances
- Do *cost-benefit* analysis when deciding to migrate...  
affinity can also be harmful, particularly when tail latency is critical



# 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  $\sum \frac{\text{CPU}}{\text{period}} \leq 1$  (not counting switch time)
- **Variety of scheduling strategies**
  - E.g., first deadline first  
(works if schedulable, otherwise fails spectacularly)

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# 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*  $E_i = A_i - (\text{warp}_i \cdot W_i : 0)$
  - Special warp factor allows borrowing against future CPU time  
...hence name of algorithm

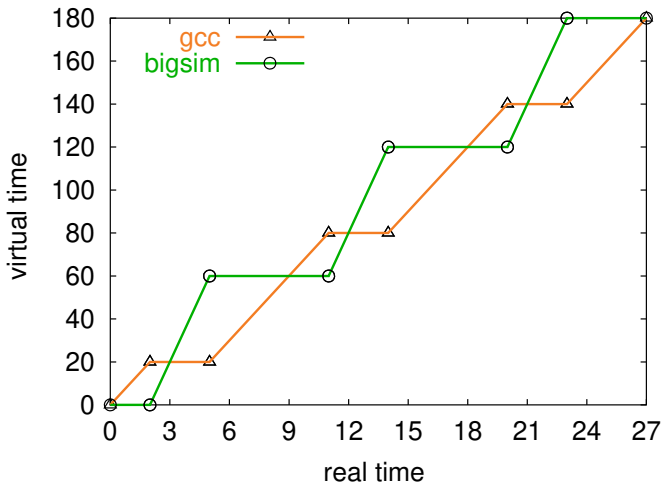
# Process weights

- Each process  $i$ 's fraction of CPU determined by weight  $w_i$ 
  - $i$  should get  $w_i / \sum_j w_j$  fraction 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 runnable... 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 runnable to avoid affecting response time

# BVT example



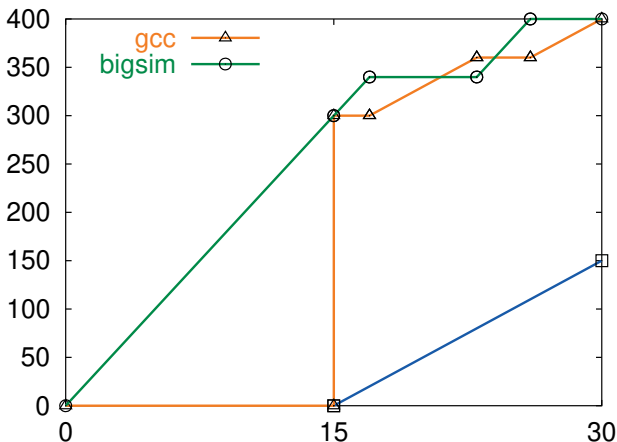
- gcc has weight 2, bigsim weight 1,  $C = 2$ , no I/O
  - bigsim consumes virtual time at twice the rate of gcc
  - Processes run for  $C$  time after lines cross before context switch

# 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

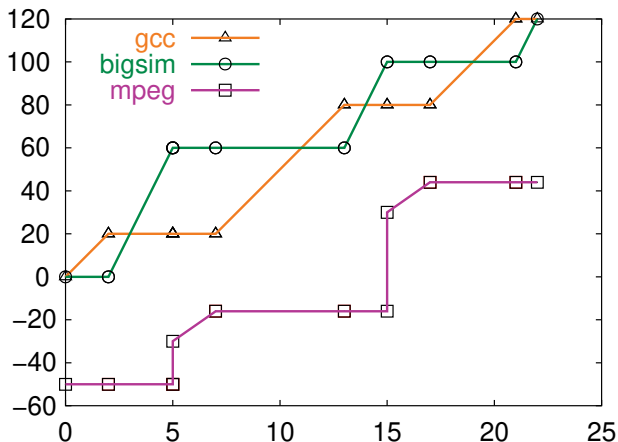


- gcc's  $A_i$  gets reset to SVT on wakeup
  - Otherwise, would be at lower (blue) line and starve bigsim

# Real-time threads

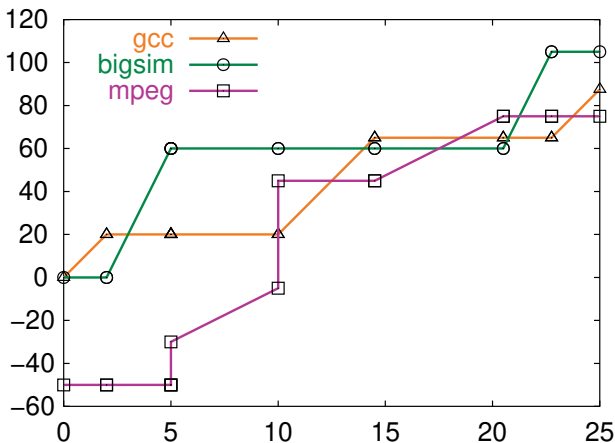
- **Also want to support time-critical tasks**
  - E.g., mpeg player must run every 10 clock ticks
- **Recall  $E_i = A_i - (\text{warp}_i ? W_i : 0)$** 
  - $W_i$  is *warp factor* – gives thread precedence
  - Just give mpeg player  $i$  large  $W_i$  factor
  - Will get CPU whenever it is runnable
  - But long term CPU share won't exceed  $w_i / \sum_j w_j$
- **Note  $W_i$  only matters when  $\text{warp}_i$  is true**
  - Can set  $\text{warp}_i$  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  $\text{warp}_i \leftarrow \text{false}$

# 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  $A_j - \text{warp}_j > A_i$ .
  - 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 =  $\langle \textit{priority}, \textit{BVFT} \rangle$  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