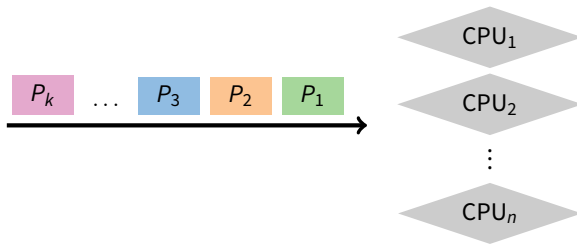


CPU scheduling



- **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)?

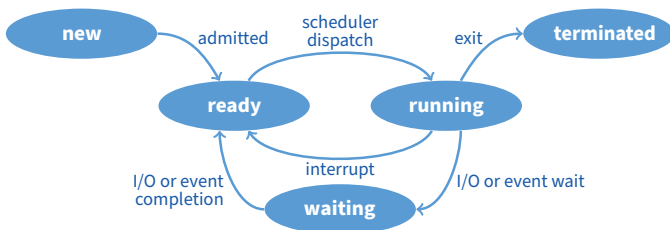
1 / 45

Outline

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

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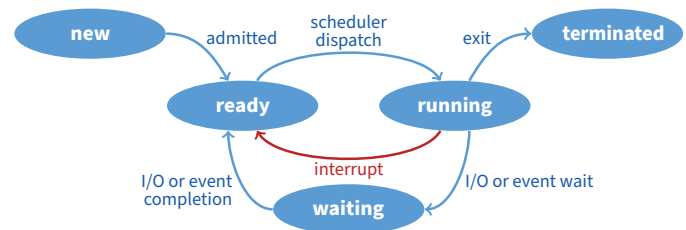
When do we schedule CPU?



- **Scheduling decisions may take place when a process:**
 1. Switches from running to ready state
 2. Switches from new/waiting to ready
 3. Switches from running to waiting state
 4. Exits
- Non-preemptive schedulers use 3 & 4 only
- Preemptive schedulers run at all four points

3 / 45

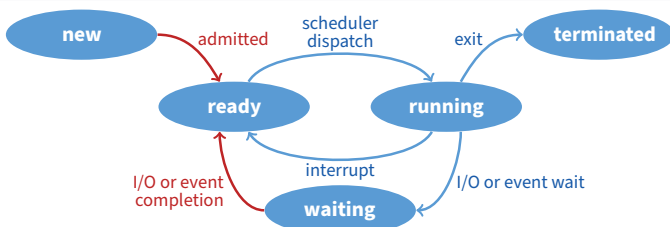
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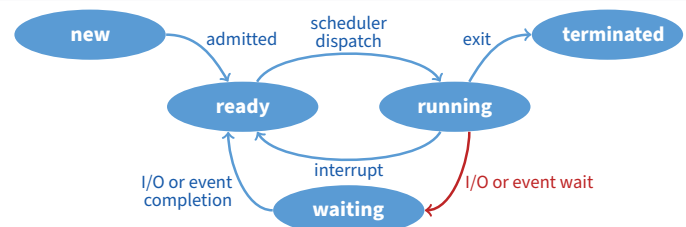
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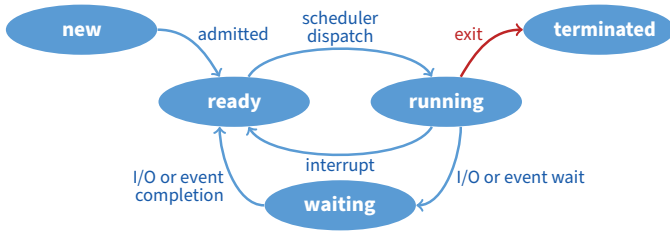
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3 / 45

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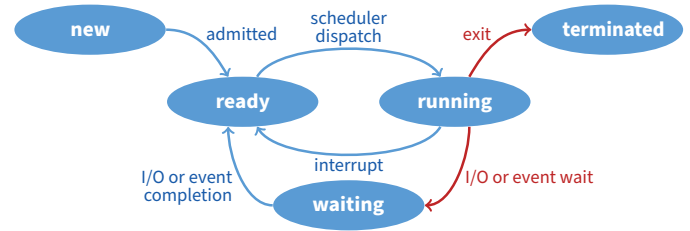
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3 / 45

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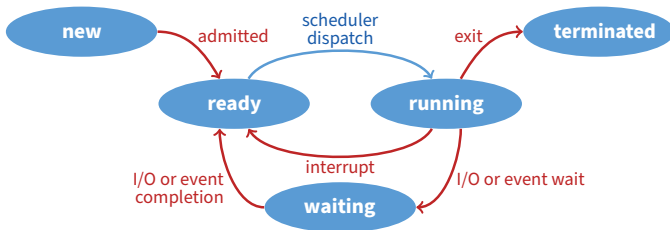
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3 / 45

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→ Preemptive schedulers run at all four points

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Scheduling criteria

- Why do we care?

- What goals should we have for a scheduling algorithm?

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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

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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:



- 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?

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FCFS continued

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

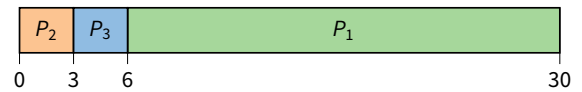


- Throughput: 3 jobs / 30 sec = 0.1 jobs/sec
- Turnaround time: $P_1 : 30, P_2 : 3, P_3 : 6$
 - Average TT: $(30 + 3 + 6)/3 = 13$ – much less than 27
- Lesson: scheduling algorithm can reduce TT
 - Minimizing waiting time can improve RT and TT
- Can a scheduling algorithm improve throughput?

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FCFS continued

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

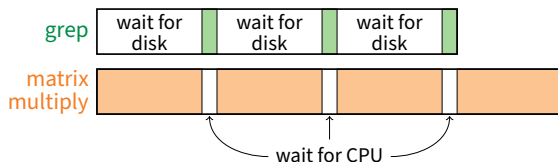


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 - Average TT: $(30 + 3 + 6)/3 = 13$ – much less than 27
- Lesson: scheduling algorithm can reduce TT
 - Minimizing waiting time can improve RT and TT
- Can a scheduling algorithm improve throughput?
 - Yes, if jobs require both computation and I/O

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View CPU and I/O devices the same

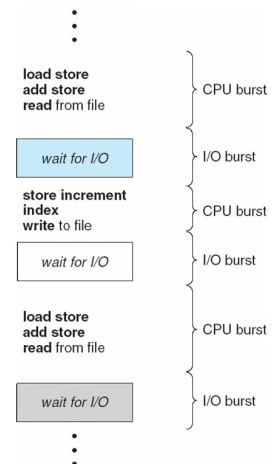
- CPU is one of several devices needed by users' jobs
 - CPU runs compute jobs, Disk drive runs disk jobs, etc.
 - With network, part of job may run on remote CPU
- Scheduling 1-CPU system with n I/O devices like scheduling asymmetric $(n + 1)$ -CPU multiprocessor
 - Result: all I/O devices + CPU busy $\implies (n + 1)$ -fold throughput gain!
- Example: disk-bound grep + CPU-bound matrix multiply
 - Overlap them just right? throughput will be almost doubled



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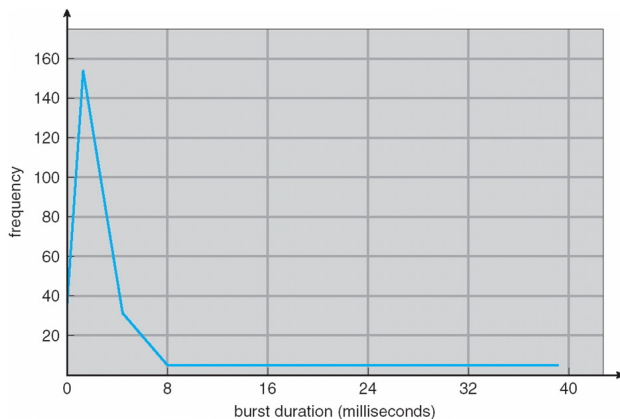
Bursts of computation & I/O

- 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



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Histogram of CPU-burst times



- What does this mean for FCFS?

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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

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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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SJF Scheduling

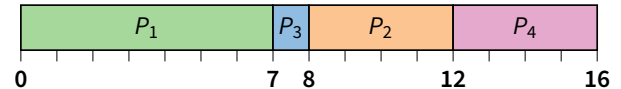
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- **What does SJF optimize?**
 - Gives minimum average *waiting time* for a given set of processes

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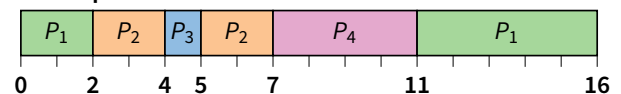
Examples

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?**

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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 $\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$

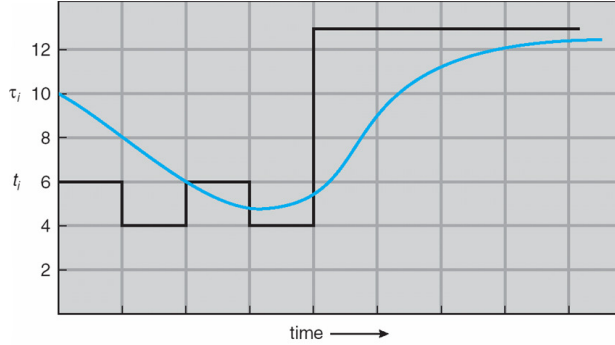
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SJF limitations

- **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**
 - Exponentially weighted average a good idea
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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	...

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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
 - (Many 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?**

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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?

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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? 199.5
 - How does that compare to FCFS? 150

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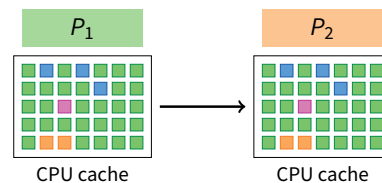
Context switch costs

- What is the cost of a context switch?

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Context switch costs

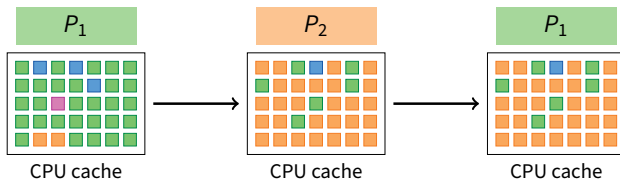
- What is the cost of a context switch?
- Brute CPU time cost in kernel
 - Save and restore registers, etc.
 - Switch address spaces (expensive instructions)
- Indirect costs: cache, buffer cache, & TLB misses



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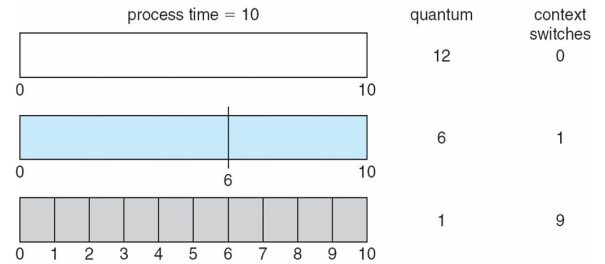
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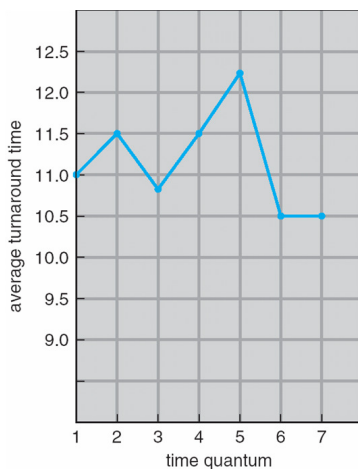
Time quantum



- 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

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Turnaround time vs. quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

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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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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?

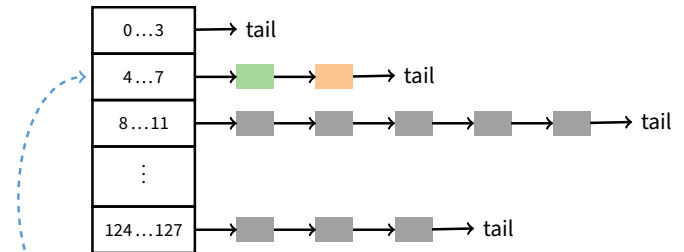
22 / 45

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- Note SJF is priority scheduling where priority is the predicted next CPU burst time
- Starvation – low priority processes may never execute
- Solution?
 - Aging: increase a process's priority as it waits

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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

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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

$$p_estcpu \leftarrow \left(\frac{2 \cdot \text{load}}{2 \cdot \text{load} + 1} \right) p_estcpu + p_nice$$

- 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)

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

¹See library.stanford.edu for off-campus access

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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:

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

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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)

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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
 - Naive priority schemes violate this

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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, \dots, M_{1000} (all prio 4)
 - L has ℓ , and M_1, \dots, M_{1000} all block on ℓ . L 's priority is $\max(L, M_1, \dots, M_{1000}) = 4$.

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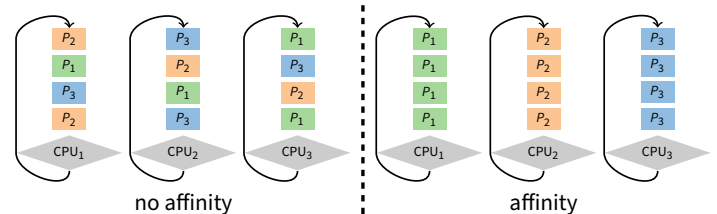
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Multiprocessor scheduling issues

- 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

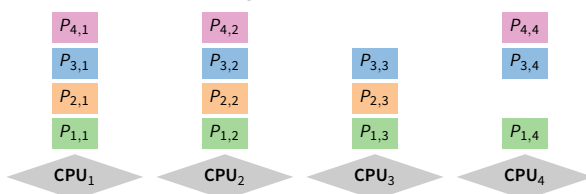


- But also prevent load imbalances
- Do *cost-benefit* analysis when deciding to migrate... affinity can also be harmful, when tail latency is critical

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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



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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)

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

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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?

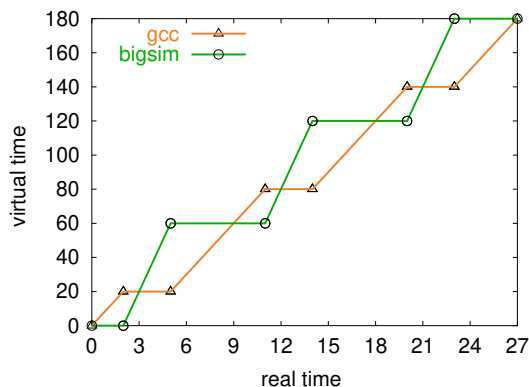
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- Add in context switch allowance, C
 - Only switch from i to j if $E_j \leq E_i - C/w_i$
 - C is wall-clock time (\gg context switch cost), so must divide by w_i
 - Ignore C if j just became runnable to avoid affecting response time

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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

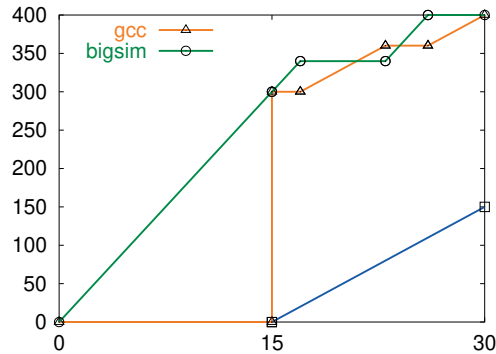
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Sleep/wakeup

- 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_i 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_i 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

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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

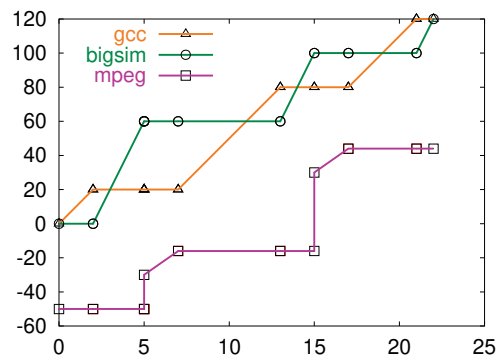
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Real-time threads

- 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 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

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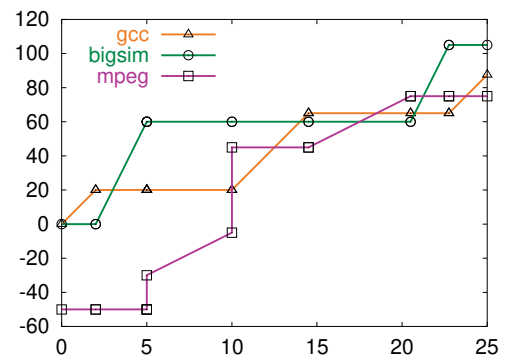
Running warped



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

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Warped thread hogging CPU



- mpeg goes into tight loop at time 5
- Exceeds L_i at time 10, so warp _{i} ← false

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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

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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 = $\langle \text{priority}, \text{BVFT} \rangle$ 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)

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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