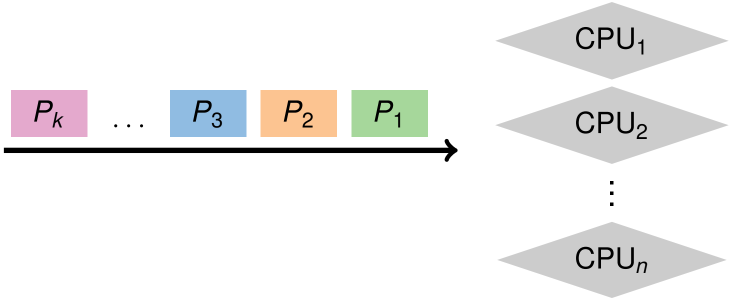
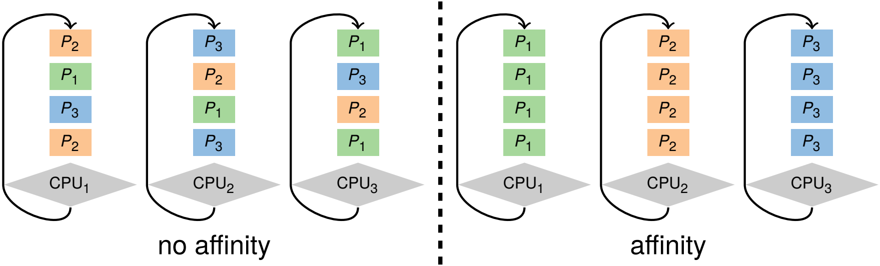
CPU scheduling



- 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)?

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 architecture 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

Outline

1. Lottery Scheduling
2. Stride Scheduling
3. Virtual Time Scheduler

Recall Limitations of BSD scheduler

- Mostly apply to $< 2.6.23$ Linux schedulers, too
- Hard to have isolation / prevent interference
    - Priorities are absolute
- Can't donate CPU (e.g., to server on RPC)
- No flexible control
    - E.g., In monte carlo simulations, error is $1/\sqrt{N}$ after N trials
    - Want to get quick estimate from new computation
    - Leave a bunch running for a while to get more accurate results
- Multimedia applications
    - Often fall back to degraded quality levels depending on resources
    - Want to control quality of different streams

Lottery scheduling [Waldspurger'94]

- Inspired by economics & free markets
- Issue lottery tickets to processes
  - By analogy with FQ, #tickets expresses a process's weight
  - Let p_i have t_i tickets
  - Let T be total # of tickets, $T = \sum_i t_i$
  - Chance of winning next quantum is t_i / T.
  - Note tickets not used up by lottery (more like season tickets)
- Control expected proportion of CPU for each process
- Can also group processes hierarchically for control
  - Subdivide lottery tickets allocated to a particular process
  - Modeled as currencies, funded through other currencies

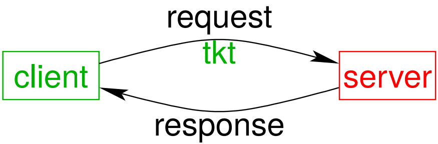
Grace under load change

- Adding/deleting jobs affects all proportionally
- Example
  - 4 jobs, 1 ticket each, each job 1/4 of CPU

  - Delete one job, each remaining one gets 1/3 of CPU

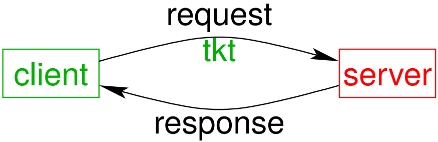
- A little bit like priority scheduling
  - More tickets means higher priority
- But with even one ticket, won't starve
  - Don't have to worry about absolute priority problem (e.g., where adding one high-priority job starves everyone)

Lottery ticket transfer



- Can *transfer* tickets to other processes
- Perfect for IPC (Inter-Process Communication)
  - Client sends request to server
  - Client will block until server sends response
  - So temporarily donate tickets to server
- Also avoids priority inversion
- How do ticket donation and priority donation differ?

Lottery ticket transfer



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- Also avoids priority inversion
- How do ticket donation and priority donation differ?
  - Consider case of 1,000 equally important processes
  - With priority, no difference between 1 and 1,000 donations
  - With tickets, recipient amasses more and more tickets

Compensation tickets

- What if process only uses fraction f of quantum?
  - Say A and B have same number of lottery tickets
  - Proc. A uses full quantum, proc. B uses f fraction
  - Each wins the lottery as often
  - B gets fraction f of B's CPU time. No fair!
- Solution: Compensation tickets
  - Say B uses fraction f of quantum
  - Inflate B's tickets by $1/f$ until it next wins CPU
  - E.g., if B always uses half a quantum, it should get scheduled twice as often on average
  - Helps maximize I/O utilization
    (remember matrix multiply vs. grep from last lecture)

Limitations of lottery scheduling

- Unpredictable latencies
- Expected errors $\sim sqrt(n_a)$ for n_a allocations
  - E.g., process *A* should have had 1/3 of CPU yet after 1 minute has had only 19 seconds
- Useful to distinguish two types of error:
  - *Absolute error* – absolute value of *A*'s error (1 sec)
  - *Relative error* – *A*'s error considering only 2 processes, *A* and *B*
- Probability of getting *k* of *n* quanta is binomial distribution
  - $\binom{n}{k}p^k(1-p)^{n-k}$ $\left[p = \text{fraction tickets owned}, \binom{n}{k} = \frac{n!}{(k!(n-k)!)}\right]$
  - For large *n*, binomial distribution approximately normal
  - Expected value is *p*, Variance for a single allocation: $p(1-p)^2 + (1-p)p^2 = p(1-p)(1-p+p) = p(1-p)$
  - Variance for *n* allocations = $np(1-p)$, stddev $\sim \sqrt{n}$

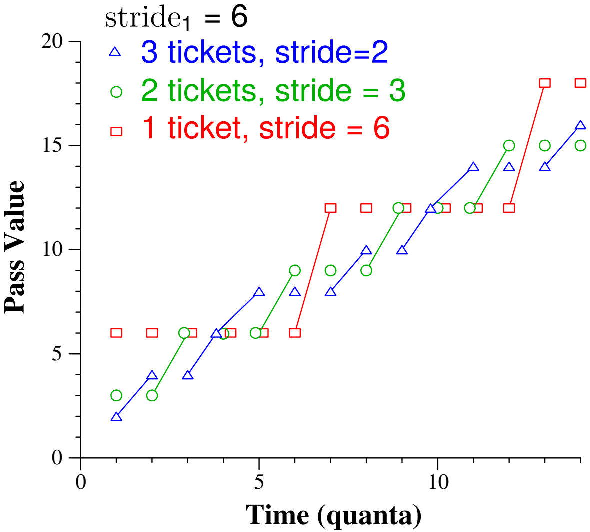
Outline

1. Lottery Scheduling
2. Stride Scheduling
3. Virtual Time Scheduler

Stride scheduling [Waldspurger'95]

- Idea: Apply ideas from weighted fair queuing
  - Deterministically achieve similar goals to lottery scheduling
- For each process, track:
  - tickets – priority (weight) assigned by administrator
  - stride $\approx 1/\mathrm{tickets}$ – speed of virtual time while process has CPU
  - pass – cumulative virtual CPU time used by process
- Schedule process *c* with lowest pass
- Then increase: `c->pass += c->stride`
- Note, can't use floating point in the kernel
  - Saving FP regs too expensive, so make stride & pass integers
  - Let stride_1 be largish integer (stride for 1 ticket)
  - Really set $\mathrm{stride} = \mathrm{stride}_1/\mathrm{tickets}$

Stride scheduling example



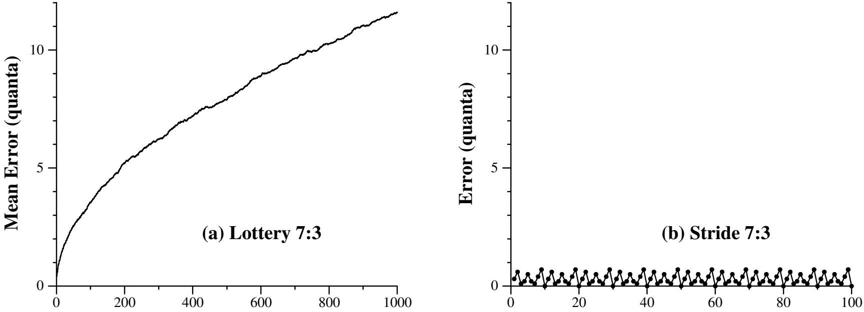
Stride vs. lottery

- Stride offers many advantages of lottery scheduling
  - Good control over resource allocation
  - Can transfer tickets to avoid priority inversion
  - Use inflation/currencies for users to control their CPU fraction
- What are stride's absolute & relative error?

Stride vs. lottery

- Stride offers many advantages of lottery scheduling
  - Good control over resource allocation
  - Can transfer tickets to avoid priority inversion
  - Use inflation/currencies for users to control their CPU fraction
- What are stride's absolute & relative error?
- Stride Relative error always ≤ 1 quantum
  - E.g., say A, B have same number of tickets
  - B has had CPU for one more time quantum than A
  - B will have larger pass, so A will get scheduled first
- Stride absolute error $\leq n$ quanta if n processes in system
  - E.g., 100 processes each with 1 ticket
  - After 99 quanta, one of them still will not have gotten CPU

Simulation results



- Can clearly see $\sqrt{n}$ factor for lottery
- Stride doing much better

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Advanced 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* $E_i = A_i - (\mathrm{warp}_i\ ?\ W_i : 0)$
  - 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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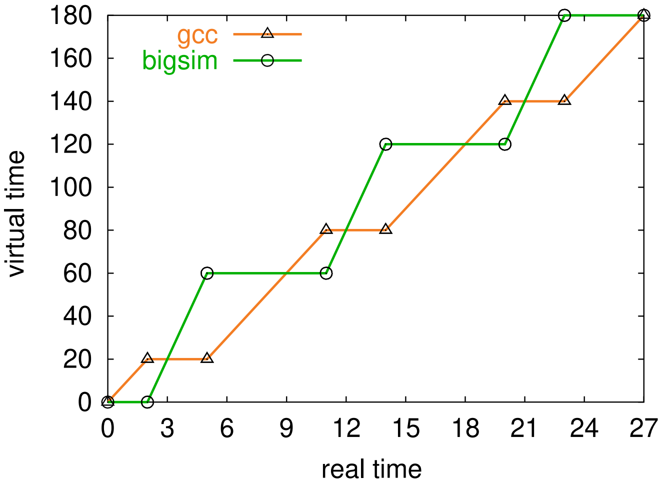
  - C is wall-clock time ($\gg$ context switch cost), so must divide by w_i
  - Ignore C if j just became runable to avoid affecting response time

BVT example

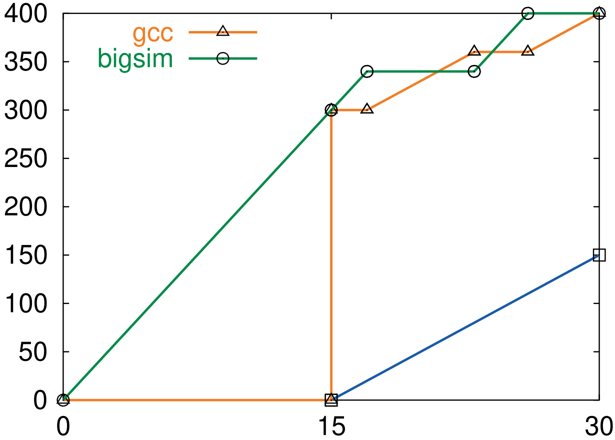


- gcc has weight 2, bigsim weight 1, *C* = 2, no I/O
  - bigsim consumes virtual time at twice the rate of gcc
  - Processes run for *C* time after lines cross before context switch

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

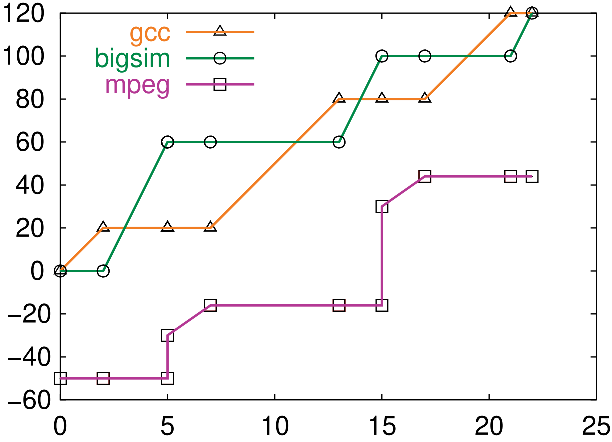


- gcc's A_i gets reset to SVT on wakeup
    - Otherwise, would be at lower (blue) line and starve bigsim

Real-time threads

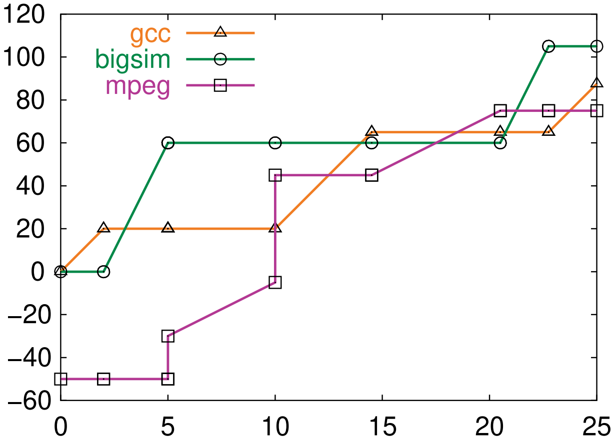
- Also want to support time-critical tasks
  - E.g., mpeg player must run every 10 clock ticks
- Recall $E_i = A_i - (\text{warp}_i \text{ ? } W_i : 0)$
  - W_i is *warp factor* – gives thread precedence
  - Just give mpeg player *i* large W_i factor
  - Will get CPU whenever it is runable
  - But long 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 a value sufficient to process fast query (e.g., 50)
- Example 1: one 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
- Example 2: one 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

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)