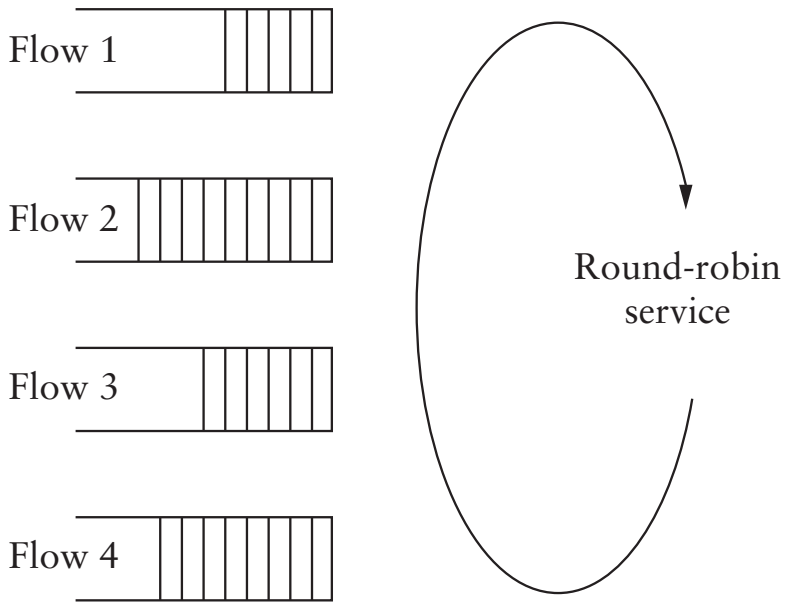
Administrivia

- **Project 1 due Friday noon**
- **If you need longer, email cs140-staff.**
  - Put "extension" in the subject
  - Tell us where you are, and how much longer you need.
  - We will give short extensions to people who don't abuse this
- **Section Friday to go over project 2**
- **Project 2 Due Friday, Feb. 7 at noon**
- **Midterm following Monday, Feb. 10**
- **Midterm will be open book, open notes**
  - Feel free to bring textbook, printouts of slides
  - Laptop computers or other electronic devices prohibited

Fair Queuing (FQ) [Demers]

- **Digression: packet scheduling problem**
  - Which network packet should router send next over a link?
  - Problem inspired some algorithms we will see today
  - Plus good to reinforce concepts in a different domain...
- **For ideal fairness, would use bit-by-bit round-robin (BR)**
  - Or send more bits from more important flows
    (flow importance can be expressed by assigning numeric *weights*)



Packet scheduling

- **Differences from CPU scheduling**
  - No preemption or yielding—must send whole packets
    - Thus, *can't* send one bit at a time
  - But know how many bits are in each packet
    - Can see the future and know how long packet needs link
- **What scheduling algorithm does this suggest?**

Packet scheduling

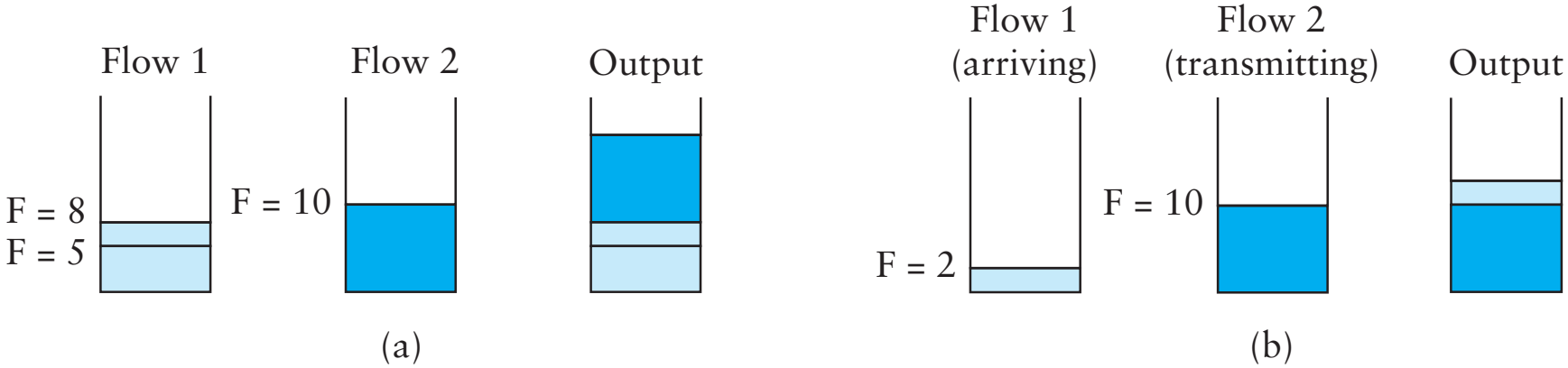
- **Differences from CPU scheduling**
  - No preemption or yielding—must send whole packets
    - Thus, *can't* send one bit at a time
  - But know how many bits are in each packet
    - Can see the future and know how long packet needs link
- **What scheduling algorithm does this suggest?** *SJF*
- **Recall limitations of SJF from last lecture:**
  - Can't see the future
    - solved by packet length
  - Optimizes response time, not turnaround time
    - but these are the same when sending whole packets
  - Not fair

FQ Algorithm

- **Goal: Finish sending packets in same order as (impossible) BR**
- **Imagine a *virtual clock* with one tick per round of BR**
  - Slows down as number of non-empty queues increases
  - Let P_i^α = length of packet i in flow α
  - Let S_i^α = virtual time router starts transmitting packet i of flow α
  - Transmission will finish at virtual time $F_i^\alpha = S_i^\alpha + P_i^\alpha$
- **What is S_i^α?**
  - If i arrived before router finished sending packet $i-1$ of same flow, then immediately after last bit of $i-1$ (i.e., $S_i^\alpha = F_{i-1}^\alpha$)
  - If no current packets for this flow, then start transmitting as soon as packet arrives—call the arrival time A_i^α
- **Thus:** $F_i^\alpha = \max(F_{i-1}^\alpha, A_i^\alpha) + P_i^\alpha$

FQ Algorithm (cont)

- **Algorithm: Send packet with lowest virtual finishing time F**



- **For weighted fair queuing, assign each flow α a weight w^α**
  - Lets flow α transmit w^α bits per virtual clock tick
  - Now $F_i^\alpha = \max(F_{i-1}^\alpha, A_i^\alpha) + P_i^\alpha / w^\alpha$
- **Virtual time is a key technique in many schedulers**
  - Increases monotonically but non-uniformly with real time
  - Saves us from recomputing values (e.g., F_i^α) as jobs come and go
  - Accommodates priority by slowing down for important jobs

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

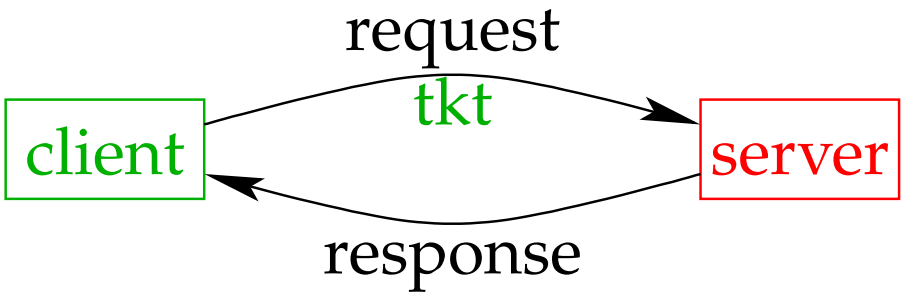
Grace under load change

- **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

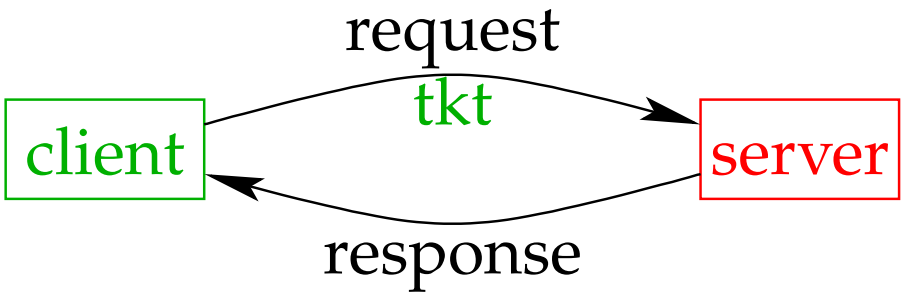
- **A little bit like priority scheduling**
  - More tickets means higher priority
- **But with even one ticket, won't starve**
  - Don't have to worry about absolute priority problem (e.g., where adding one high-priority job starves everyone)

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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  - Client sends request to server
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  - So temporarily donate tickets to server
- **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)

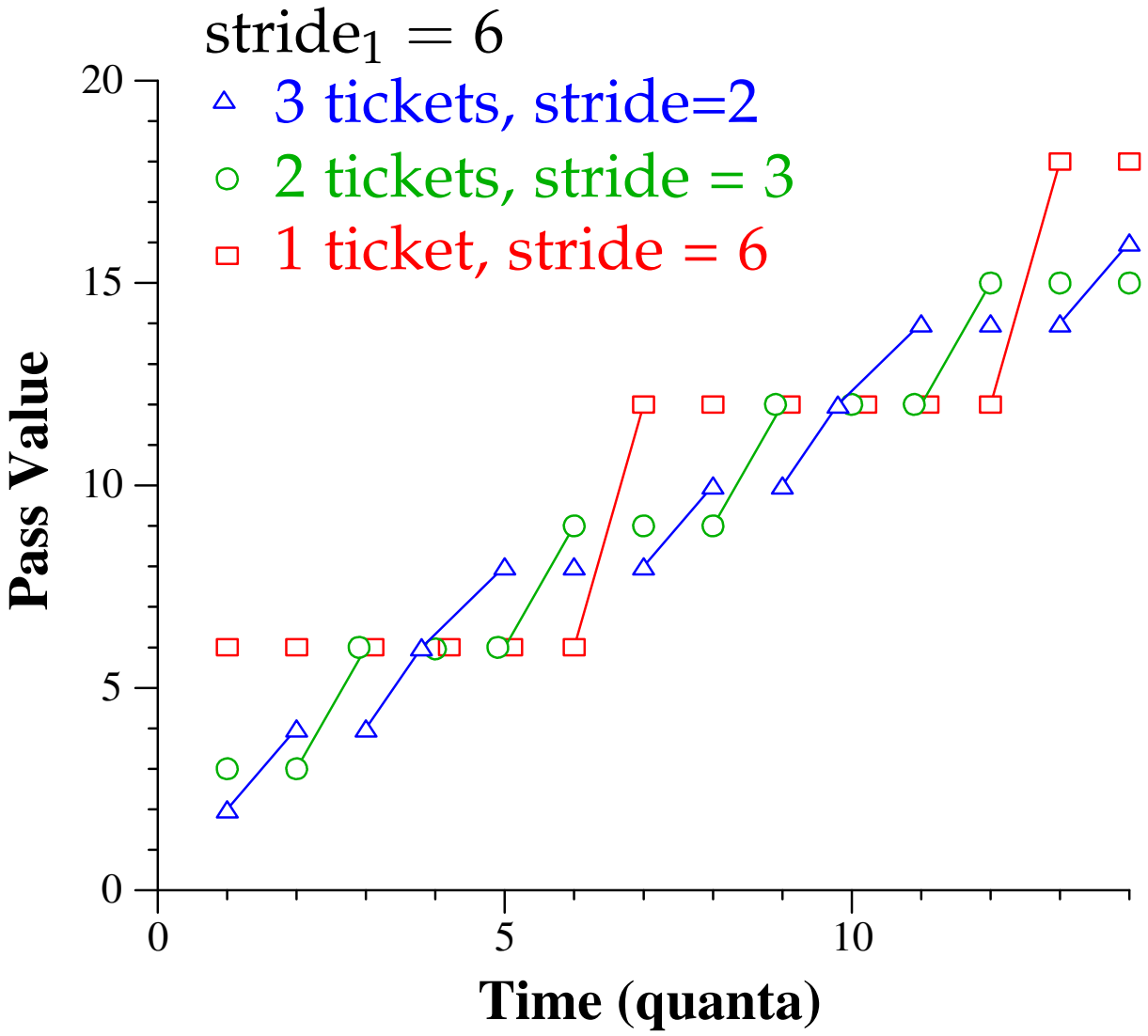
Limitations of lottery scheduling

- **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 $\sim \sqrt{n}$

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 $\approx 1/\text{tickets}$ – 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 stride $= \text{stride}_1/\text{tickets}$

Stride scheduling example



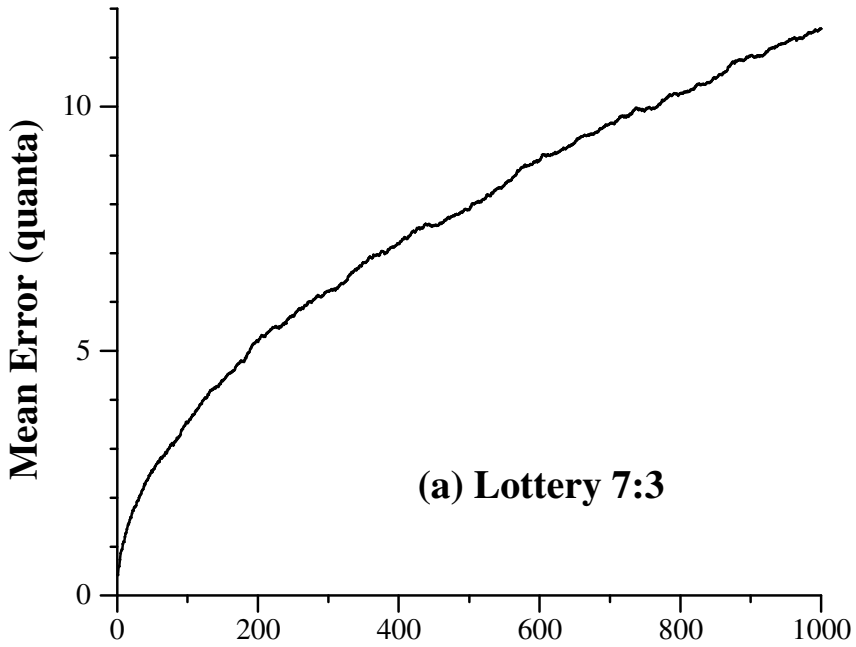
Stride vs. lottery

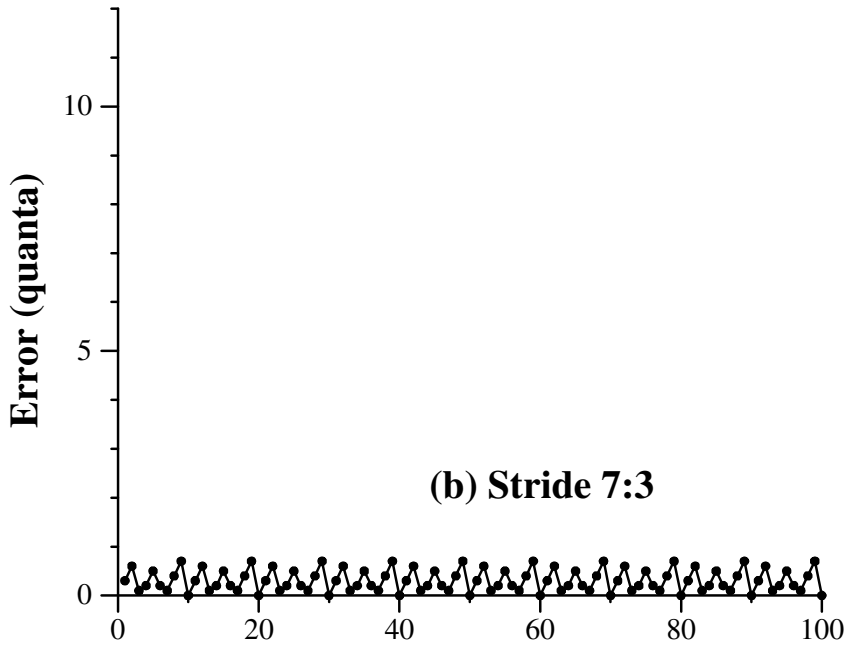
- **Stride offers many advantages of lottery scheduling**
  - Good control over resource allocation
  - Can transfer tickets to avoid priority inversion
  - Use inflation/currencies for users to control their CPU fraction
- **What are stride's absolute & relative error?**

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





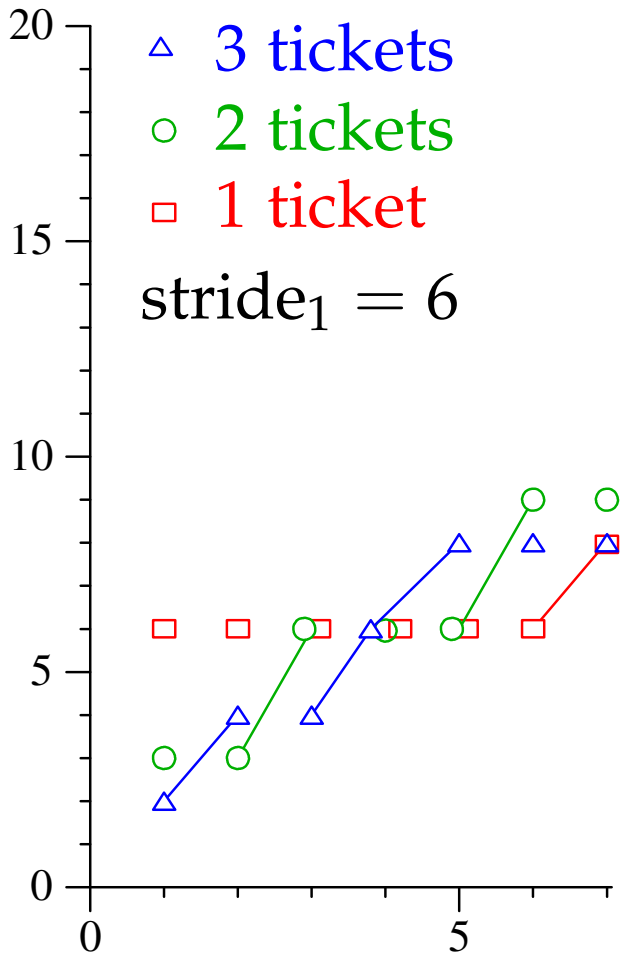
- **Can clearly see $\sqrt{n}$ factor for lottery**
- **Stride doing much better**

Stride ticket transfer

- **Want to transfer tickets like lottery**
- **Just recompute stride on transfer?**

Stride ticket transfer

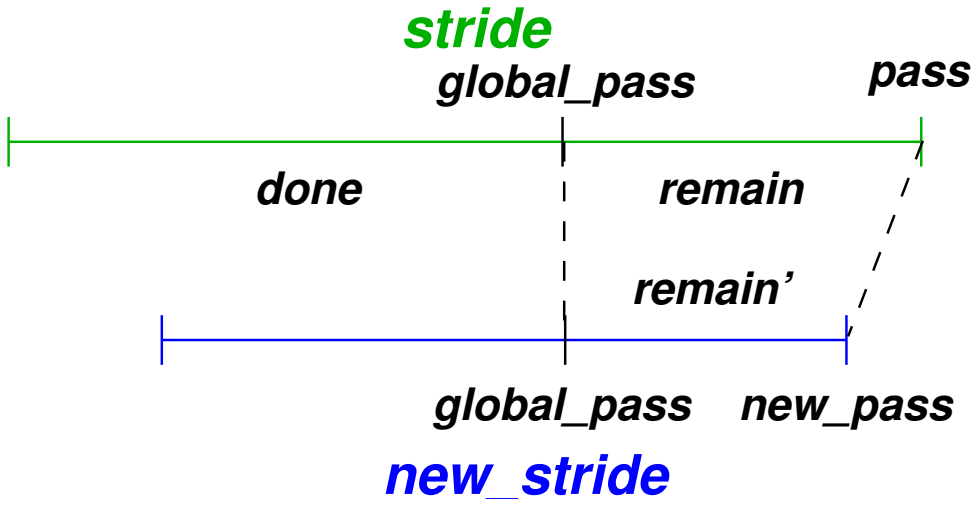
- **Want to transfer tickets like lottery**
- **Just recompute stride on transfer?**
- **No! Would mean long latency**
  - E.g., transfer 2 tickets to □ at time 0
  - Now □ has same priority as △
  - But still waits 6 seconds to run
  - Very bad for IPC latency, mutexes, etc.
- **Solution: Must scale remaining portion of pass by new # tickets**



Scaling pass value

- **Add some global variables**
  - global-tickets – # tickets held by all runable processes
  - global-stride – stride_1 / global-tickets
  - global-pass – advances by global-stride each quantum
- **On ticket transfer:**

```
c->tickets = new_tickets;
c->stride = stride1 / c->tickets
int remain = c->pass - global_pass
remain *= new_stride / old_stride
c->pass = global_pass + remain
```



Sleep/wakeup

- **Process might use only fraction f of quantum**
  - Just increment `c->pass += f * c->stride`
- **What if a process blocks or goes to sleep?**
- **Could do nothing—what's wrong with this?**

Sleep/wakeup

- **Process might use only fraction f of quantum**
  - Just increment `c->pass += f * c->stride`
- **What if a process blocks or goes to sleep?**
- **Could do nothing—what's wrong with this?**
  - Will completely monopolize CPU when it wakes up with much smaller pass value than everyone else
- **Could just revoke tickets while sleeping**
  - Use negative ticket transfer to reduce # tickets to 0
  - But code on previous slide would require division by 0
- **Instead, keep advancing at global-pass rate**
  - On sleep: `c->remain = c->pass - global_pass`
  - On wakeup: `c->pass = global_pass + c->remain`
  - Slightly weird if global-tickets varies greatly

Stride error revisited

- **Consider 101 procs w. allocations** $100 : 1 : 1 : \ldots : 1$
  - What happens?

Stride error revisited

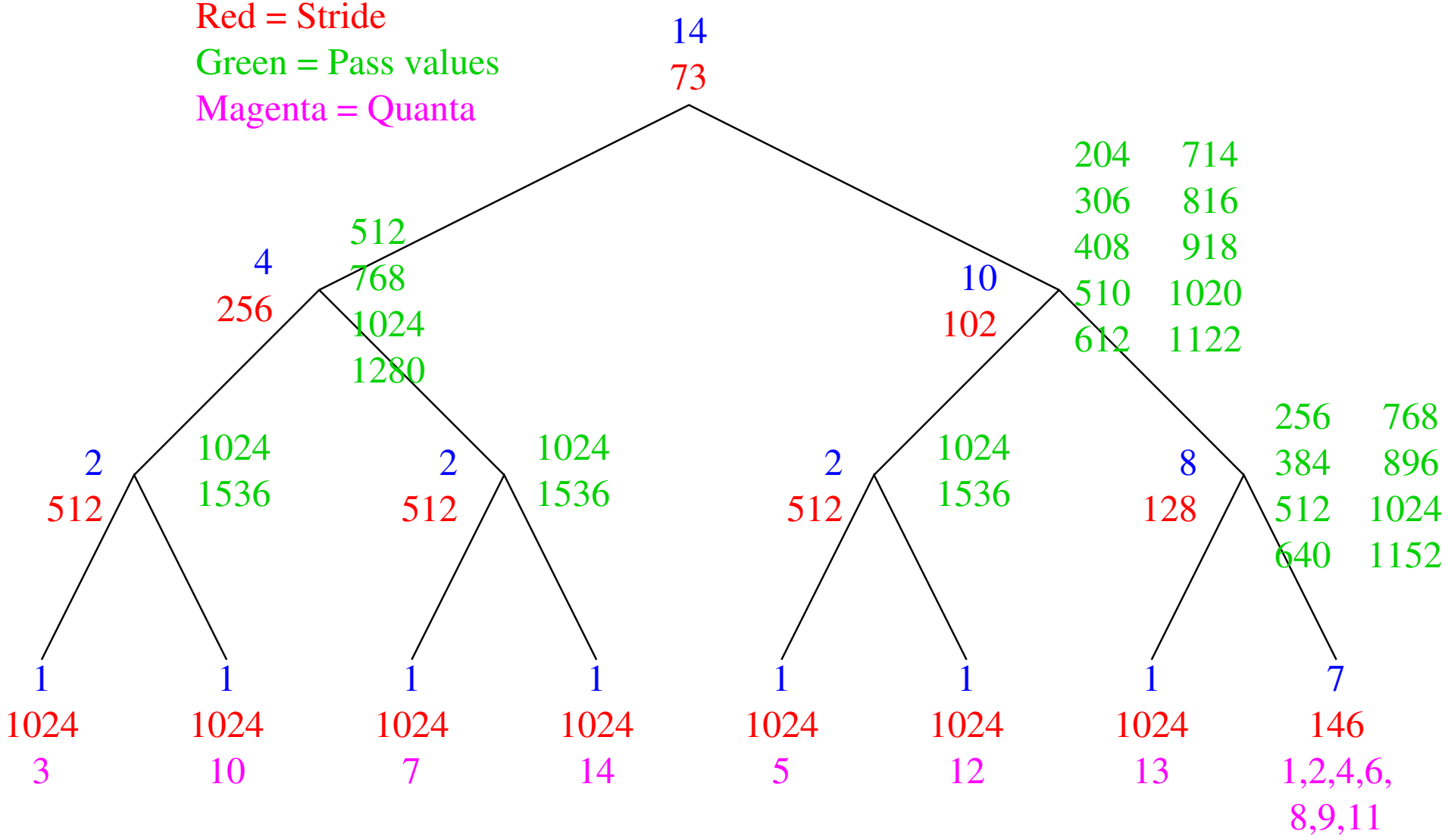
- **Consider 101 procs w. allocations** $100 : 1 : 1 : \ldots : 1$
  - Cycle where high priority P_0 gets CPU for 100 quanta
  - Then $P_1 \ldots P_{100}$ get one quanta each
- **Another scheduler might give** $P_0, P_1, P_0, P_2, P_0, \ldots$
  - Which is better?

Stride error revisited

- **Consider 101 procs w. allocations** $100 : 1 : 1 : \ldots : 1$
  - Cycle where high priority P_0 gets CPU for 100 quanta
  - Then $P_1 \ldots P_{100}$ get one quanta each
- **Another scheduler might give** $P_0, P_1, P_0, P_2, P_0, \ldots$
  - Which is better?
  - Letting P_0 run for 100 quanta reduces context switches
  - But then starving P_0 for 100 quanta increase absolute error
- **Solution: Hierarchical stride scheduling**
  - Organize processes into a tree, schedule at each level
  - Internal nodes have more tickets, so smaller strides
  - Greatly improves response time
  - Now for n procs, absolute error is $O(\log n)$, instead of $O(n)$

Hierarchical stride example

Stride1 = 1,024
Blue = Tickets
Red = Stride
Green = Pass values
Magenta = Quanta



BVT [Duda]

- **Borrowed Virtual Time (BVT)**
  - Algorithm proposed by Duda & Cheriton in 1999
- **Goals:**
  - Support mix of soft real-time and best-effort tasks
  - Simple to use (avoid 1,000,000 knobs to tweak)
  - Should be easy, efficient to implement
- **Idea: Run process w. 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 seconds per virtual time tick while i has CPU
- **When i consumes t CPU time, track it: A_i += t/w_i**
  - As with stride, pick some large N (like stride$_1$)
  - Pre-compute $m_i = N/w_i$, then set A_i += $t \cdot m_i$
- **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 real time ($\gg$ context switch cost), so must divide by w_i
  - Ignore C if j just became runable... why?

Process weights

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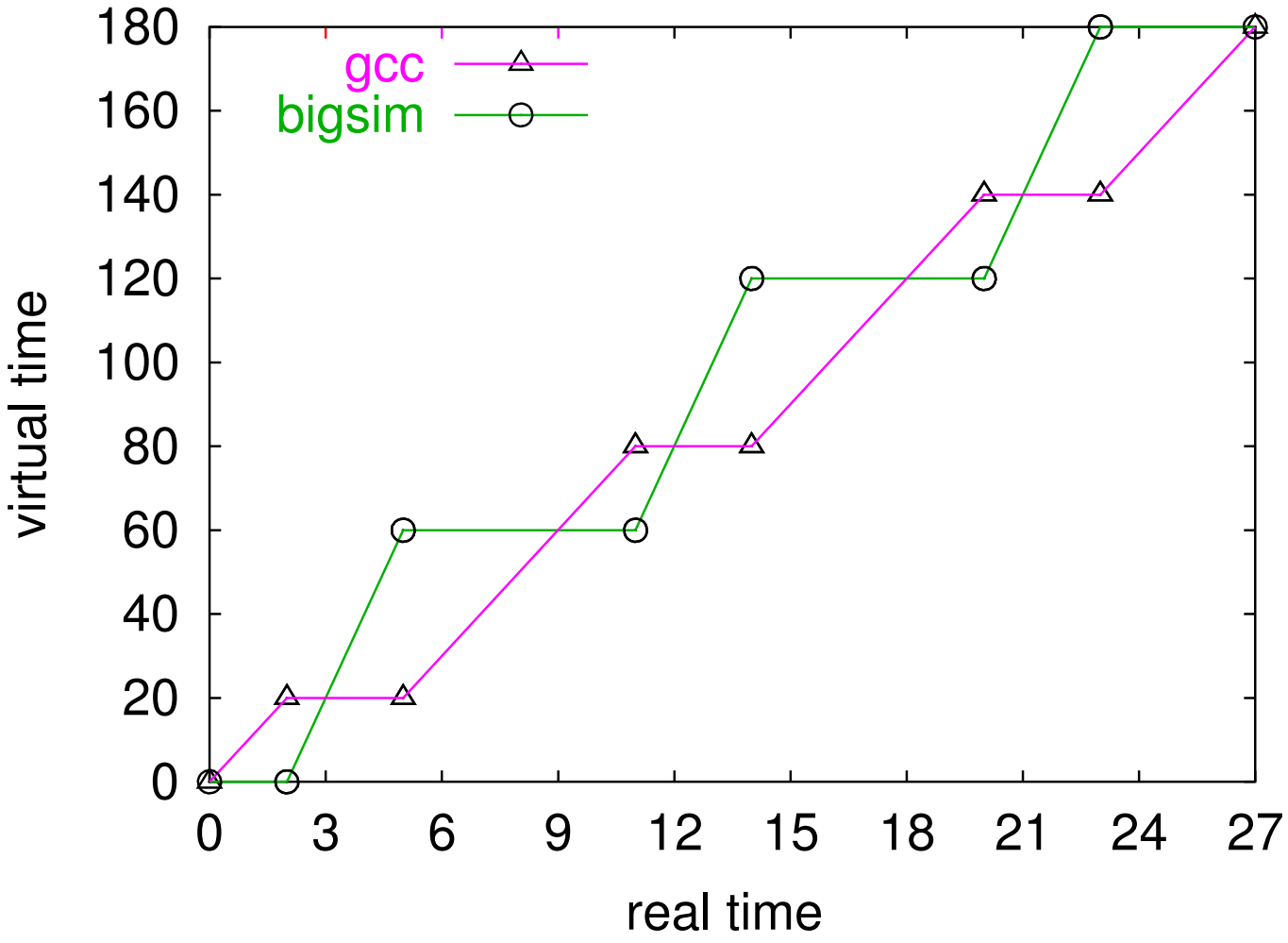
  - Ignore C if j just became runable to avoid affecting response time

BVT example

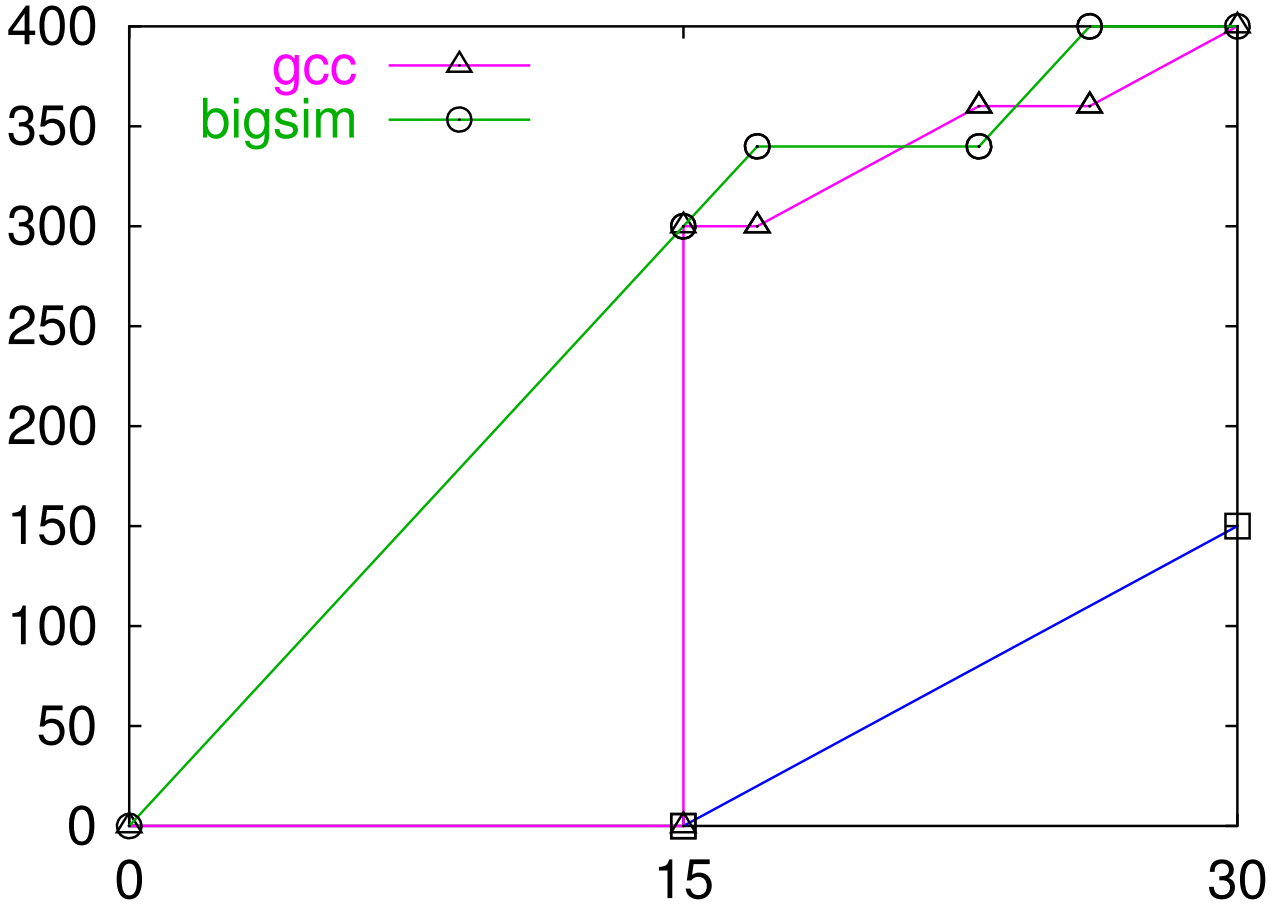


- **gcc has weight 2, bigsim weight 1,** $C = 2$**, no I/O**
  - bigsim consumes virtual time at twice the rate of gcc
  - Procs always run for C time after exceeding other's E_i

Sleep/wakeup

- **As with stride, must lower priority 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
- **Also note 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

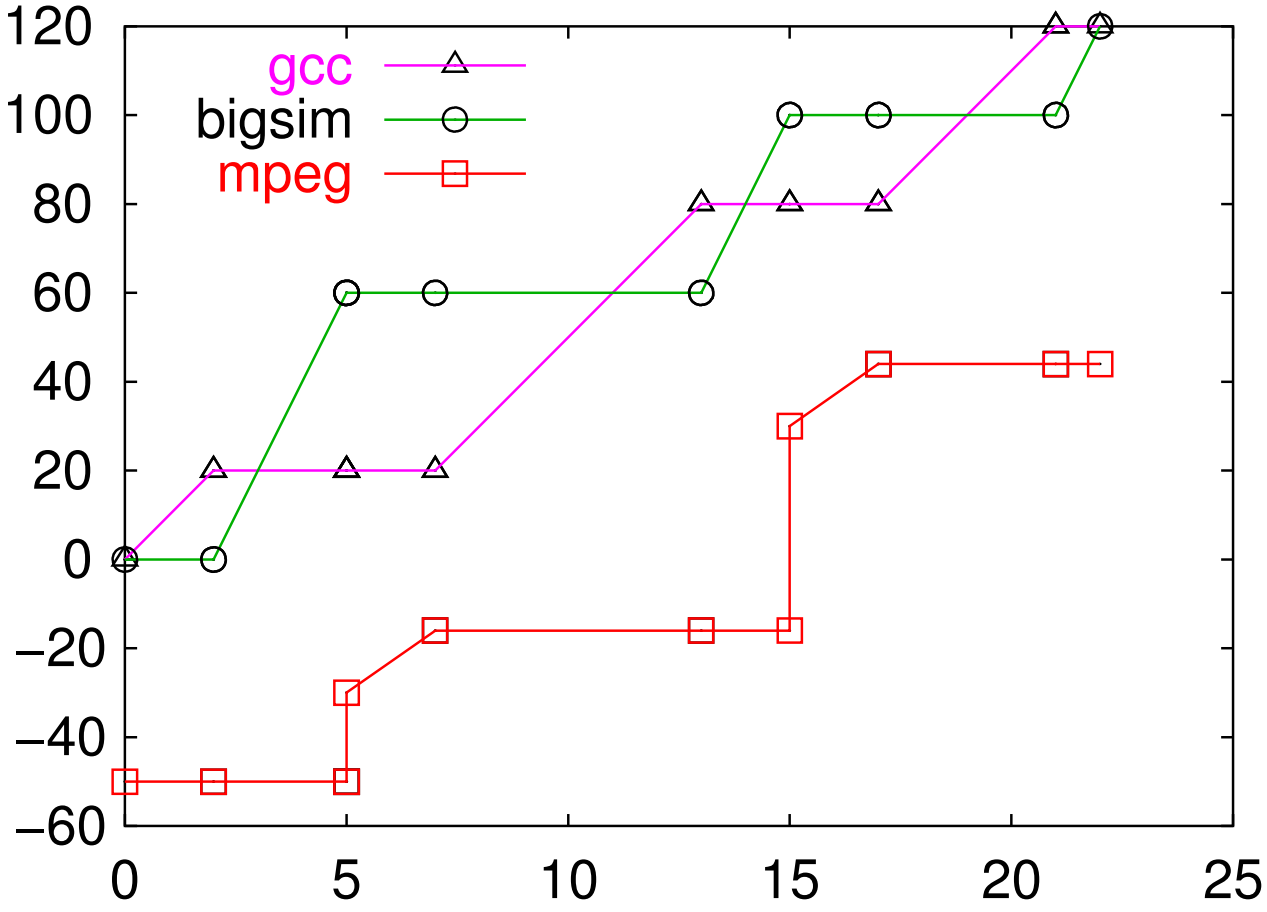


- **gcc's A_i gets reset to SVT on wakeup**
  - Otherwise, would be at lower (blue) line and starve bigsim

Real-time threads

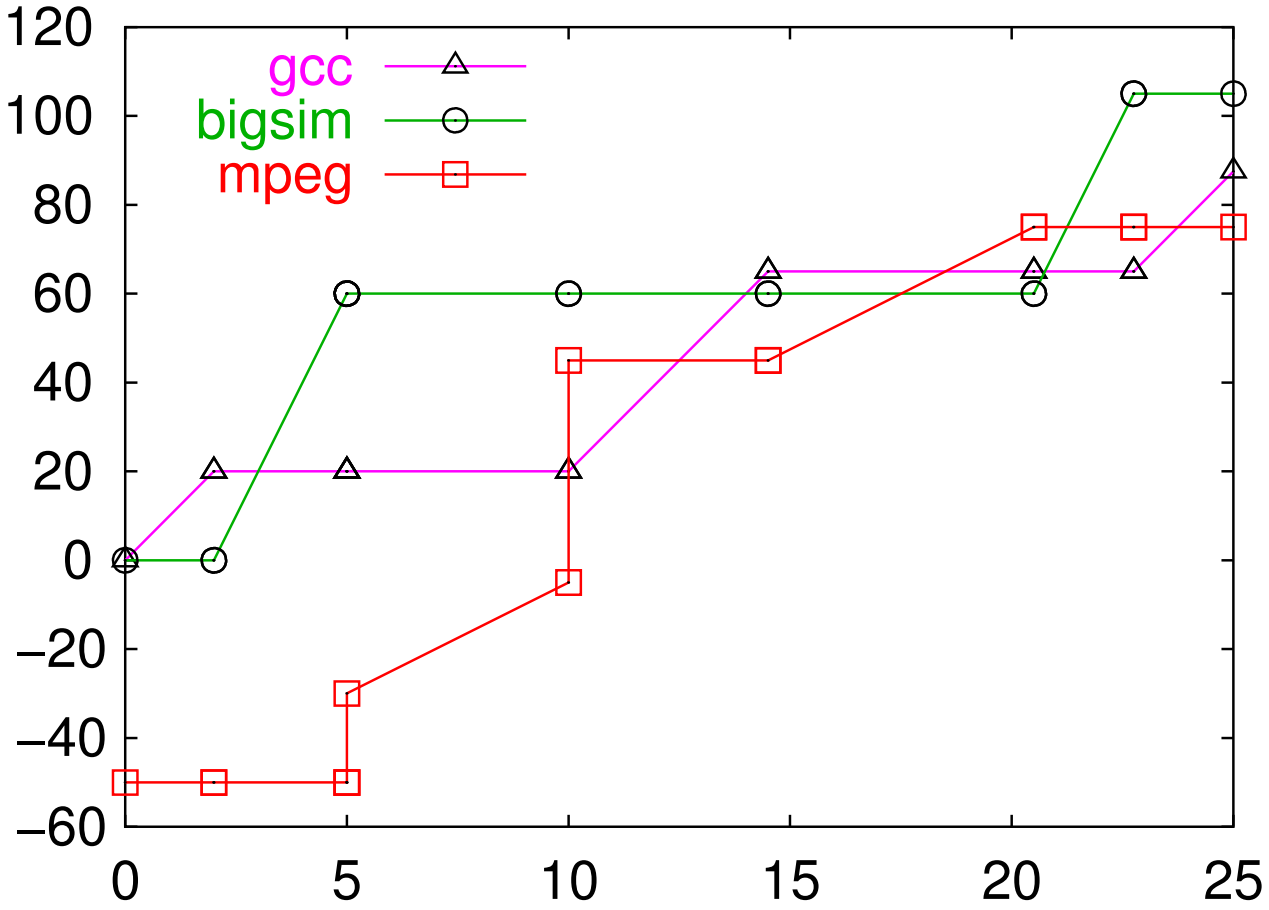
- **Also want to support soft real-time threads**
  - E.g., mpeg player must run every 10 clock ticks
- **Recall** $E_i = A_i - (\text{warp}_i \ ? \ W_i : 0)$
  - W_i is *warp factor* – gives thread precedence
  - Just give mpeg player i large W_i factor
  - Will get CPU whenever it is runable
  - But 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 it 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 $\mathrm{warp}_i \leftarrow$ false**

Google example

- **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
- **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
  - Eventually Fast query thread j gets $A_j = max(A_j, SVT) = A_j$, and eventually $A_j - \text{warp}_j > A_i$.
  - At that point thread i will run again, so no starvation

SMART [Nieh]

- **Proposed by Nieh & Lam in 1997**
- **Goals:**
  - Support soft real-time constraints
  - Coexistence w. conventional workloads
  - User preferences (e.g., watching video while waiting for a compile means video lower priority; compiling in background during a video conference is the opposite)
- **Key idea: Separate *importance* from *urgency***
  - Figure out which processes are important enough to run
  - Run whichever of these is most urgent

SMART thread properties

- **Application interface**
  - `priocntl (idtype_t idtype, id_t id, int cmd, ...);`
  - Set two properties for each thread: priority & share
  - Real-time applications can specify constraints, where $constraint = \langle deadline, estimated\ processing\ time \rangle$
- **Importance =** $\langle priority, BVFT \rangle$ **value-tuple**
  - priority is parameter set by user or administrator
  - BVFT is Biased Virtual Finishing Time
    (like fair queuing, plus bias explained on next slide)
- **To compare the importance of two threads**
  - Priority takes absolute precedence
  - If same priority, earlier BVFT more important

BVFT high-level overview

- **Each task has weighted virtual time like BVT**
- **But system keeps a queue for each priority**
  - BVT's SVT is roughly replaced by queue virtual time
  - Try to maintain fairness within each queue
  - While across queues priority is absolute
- ***Bias* factor is kind of like negative warp**
  - VFT + Bias = BVFT
  - High bias means process can tolerate short-term unfairness
  - Though in long run proportion of CPU will still be fair
  - Any user interaction sets bias to 0
  - Real-time tasks have 0 bias

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 RT task, starting from the best value-tuple**
  - Can you run it without missing deadlines of tasks w. better value-tuples?
    Yes? Add to *schedulable* set
  - Run task with earliest deadline in schedulable set
- **Send signal to tasks that won't meet their deadlines**

Current Linux

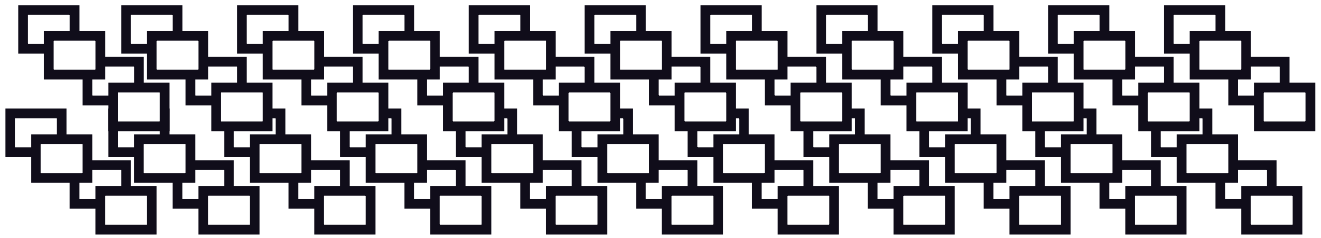
- **Linux currently has "pluggable" scheduling [LWN]**
- **Global linked list of `struct sched_class`**
  - Each `sched_class` has function ptrs implementing a scheduler
    E.g., `enqueue_task`, `pick_next_task`, `task_woken`, ...
  - Each process's `task_struct` has pointer to its `sched_class`
- **Schedulers are in strict hierarchy**
  - If `sched_class_highest` has runnable process, gets CPU
  - Otherwise, `sched_class_highest->next`, etc.
- **Not easy to plug in schedulers w/o changing source**
  - E.g., existing schedulers have dedicated fields in `task_struct`
- **Default kernel has two schedulers:**
  - Real-time (highest priority, not used unless set with *chrt*)
  - Completely Fair Scheduler [CFS]

CFS

- **Quantum depends on # of runnable processes, determined by parameters set in `/proc/sys/kernel`:**
  - `sched_latency_ns`: How often processes should run
  - `sched_min_granularity_ns`: Minimum quantum
  - Quantum $= \max\left(\frac{\texttt{sched\_latency}}{\#\,\text{runnable}}, \texttt{sched\_min\_granularity\_ns}\right)$
- **Keep stats in per-proc `sched_entity` structure**
  - `vruntime` is basically *pass* from the stride scheduler
  - Assumes nanosecond-granularity timer, simplifying things
- **Keeps per-runqueue values:**
  - `min_vruntime` is BVT's SVT (new procs get this `vruntime`)
  - Red-black tree orders procs by `vruntime` ($O(\log n)$))
  - Always run process with lowest `vruntime`
- **Extensions for hierarchical grouping w. `cgroups`**

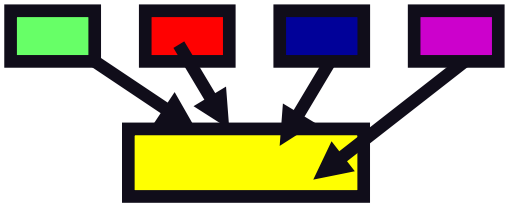
Distributed scheduling

- **Say you have a large system of independent nodes**



- **You want to run a job on a lightly loaded node**
  - Unlike single-node scheduler, don't know all machines' loads
  - Too expensive to query each node for its load
- **Instead, pick node at random**
  - This is how lots of Internet services work
- **Mitzenmacher: Then randomly pick one other one!**
  - Send job to less loaded of two randomly sampled nodes
  - Result? Really close to optimal (with a few assumptions)
  - Exponential convergence $\Longrightarrow$ picking 3 doesn't get you much

The universality of scheduling



- **General problem: Let m requests share n resources**
  - Always same issues: fairness, prioritizing, optimization
- **Disk arm: which read/write request to do next?**
  - Optimal: close requests = faster
  - Fair: don't starve far requests
- **Memory scheduling: whom to take page from?**
  - Optimal: past=future? take from least-recently-used
  - Fair: equal share of memory
- **Printer: what job to print?**
  - People = fairness paramount: uses FIFO rather than SJF
  - Use "admission control" to combat long jobs

Postscript

- **In principle, scheduling decisions can be arbitrary & shouldn't affect program's results**
  - Good, since rare that "the best" schedule can be calculated
- **In practice, schedule does affect correctness**
  - Soft real time (e.g., mpeg or other multimedia) common
  - Or after 10s of seconds, users will give up on web server
- **Unfortunately, algorithms strongly affect system throughput, turnaround time, and response time**
- **The best schemes are adaptive. To do absolutely best we'd have to predict the future.**
  - Most current algorithms tend to give the highest priority to the processes that need the least CPU time
  - Scheduling has gotten increasingly *ad hoc* over the years. 1960s papers very math heavy, now mostly "tweak and see"