CS162
Operating Systems and Systems Programming
Lecture 11

Scheduling 1: Concepts and Classic Policies

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Recall: Basic Structure of *Mesa* Monitor Program

- Monitors represent the synchronization logic of the program
  - Wait if necessary
  - Signal when change something so any waiting threads can proceed
- Basic structure of mesa monitor-based program:

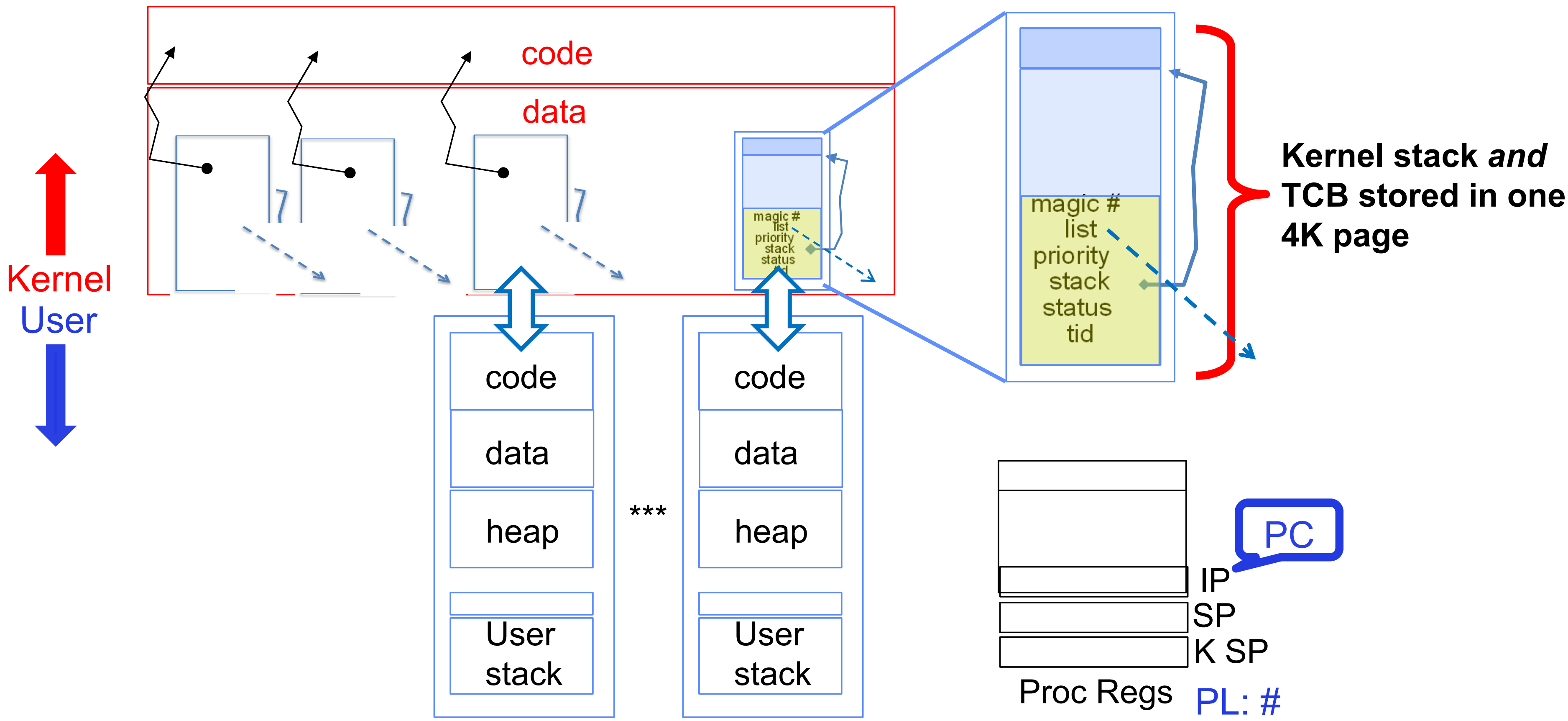
```
lock
while (need to wait) {
   condvar.wait();
}
unlock
```

Check and/or update state variables
Wait if necessary

```
do something so no need to wait

lock

condvar.signal();

unlock
```

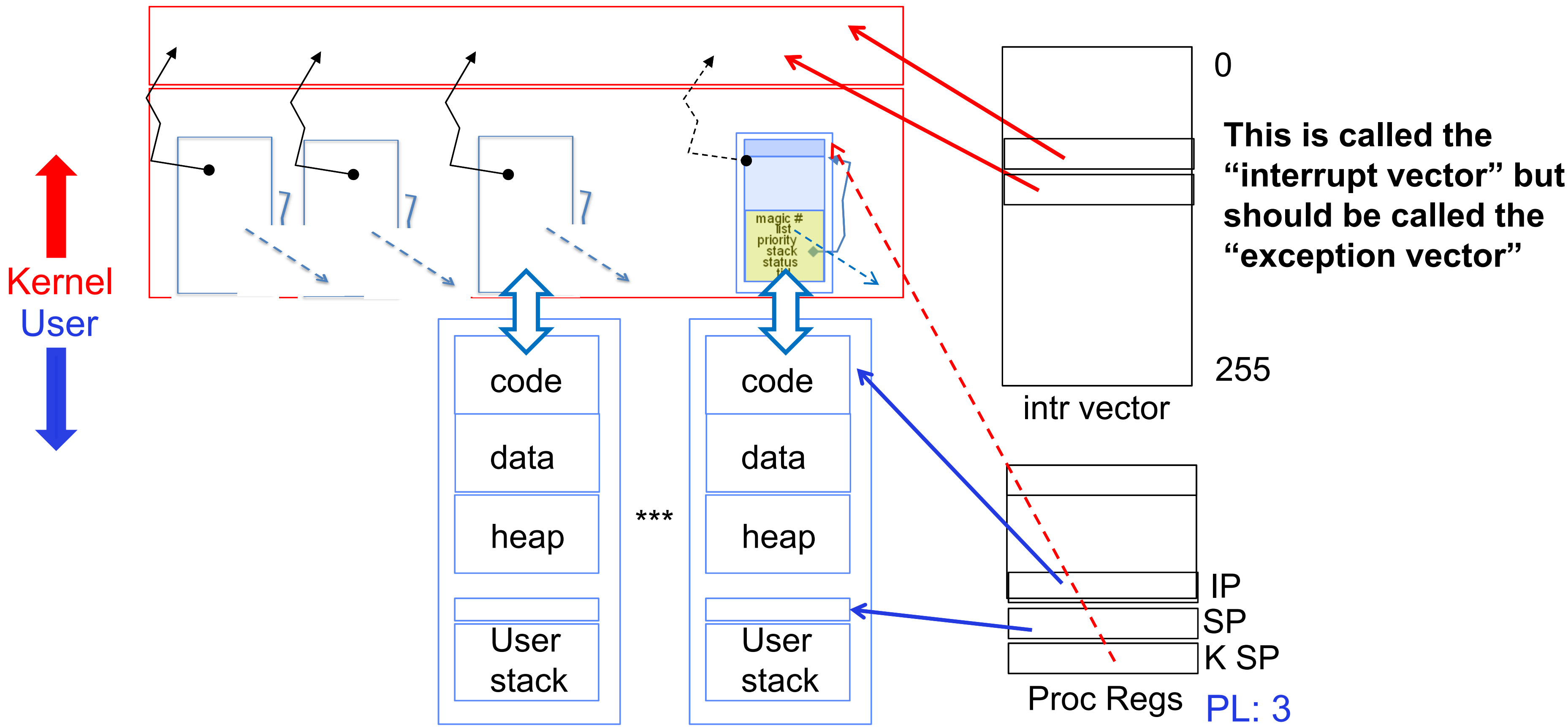
Check and/or update state variables

Recall: MT Kernel single Thread Process ala Pintos/x86



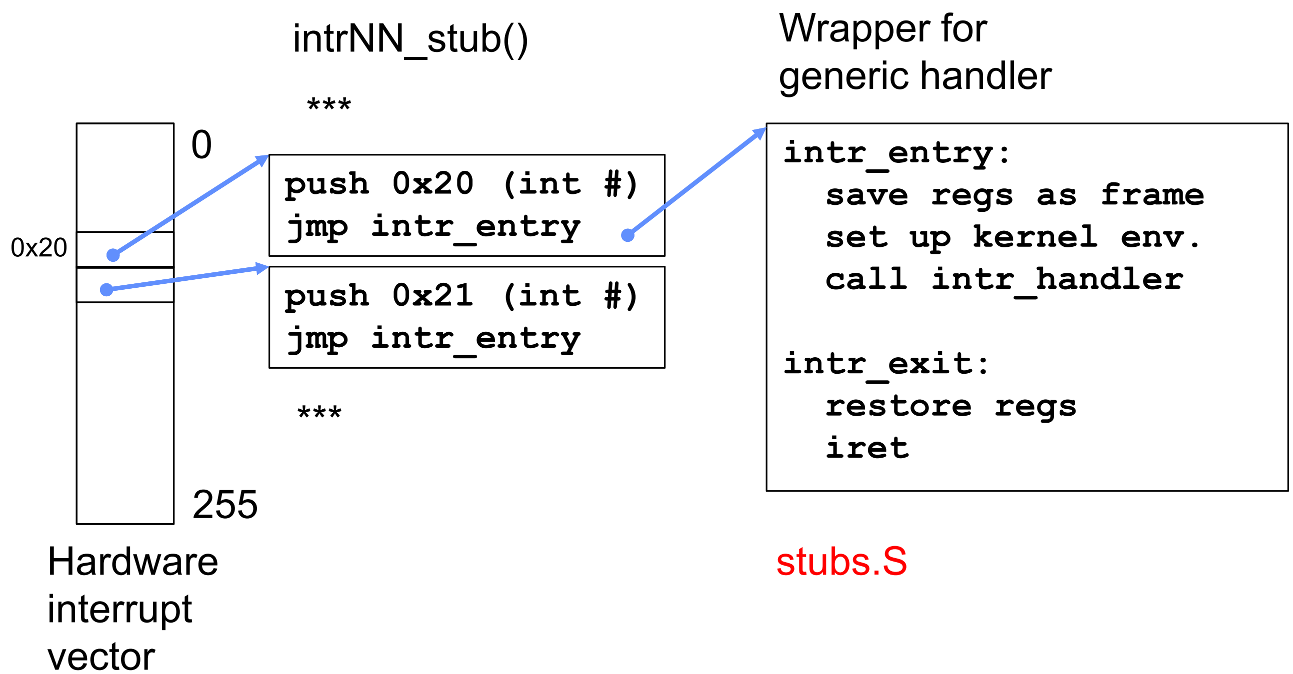
- Each user process/thread associated with a kernel thread, described by a 4KB page object containing TCB and kernel stack for the kernel thread

Recall: User → Kernel via “interrupt vector” (interrupts & traps)

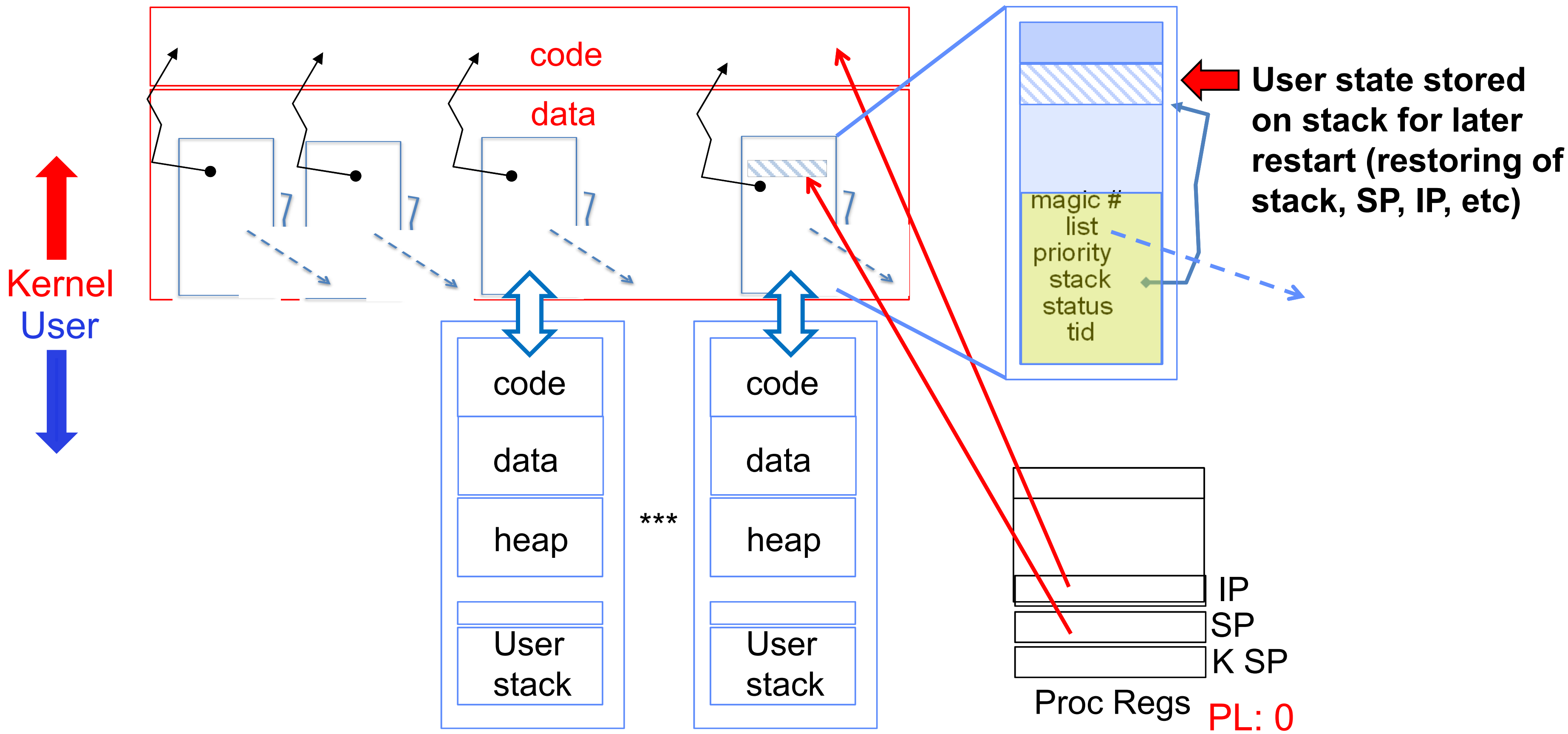


- Interrupts (timer) or trap (syscall, page fault) transfers through interrupt vector (IDT)
  - Each slot for different exception type

Pintos Interrupt Processing for Timer (0x20)

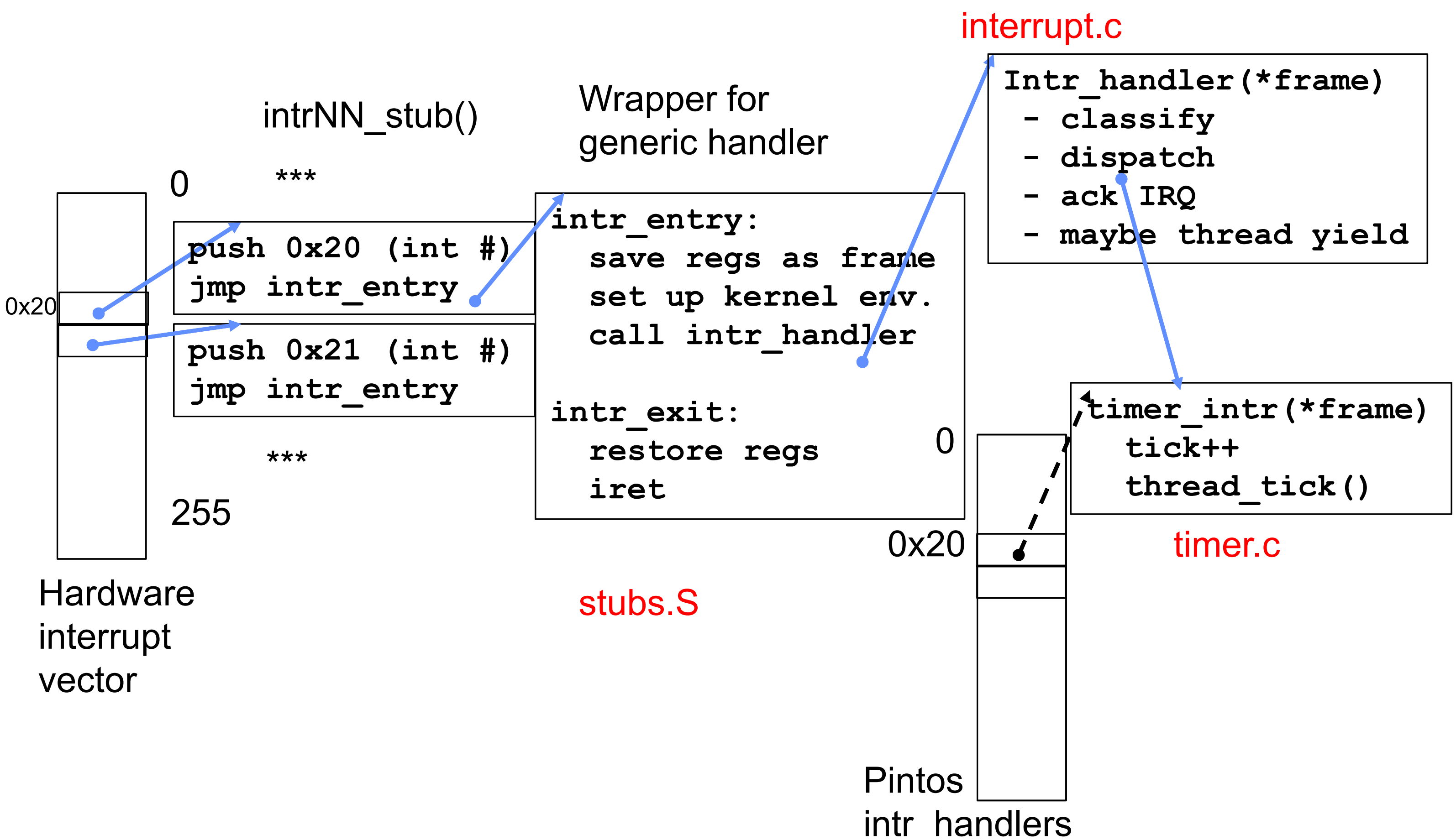


Switch to Kernel Stack for Thread



- Information required to restart thread stored on kernel stack
  – Switching becomes simple to different kernel stack and restoring

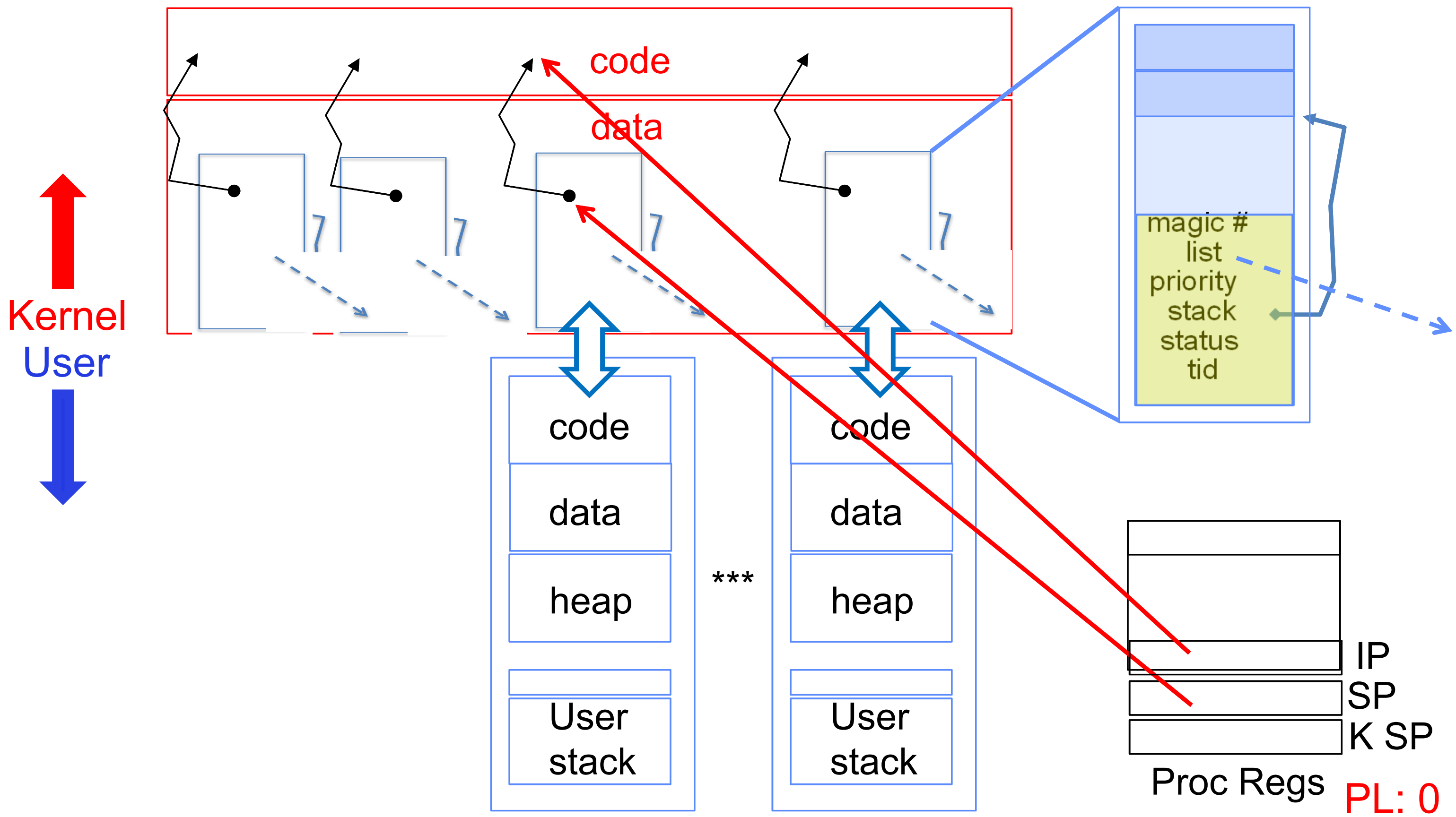
Pintos Interrupt Processing for Timer (0x20)



Timer may trigger thread switch

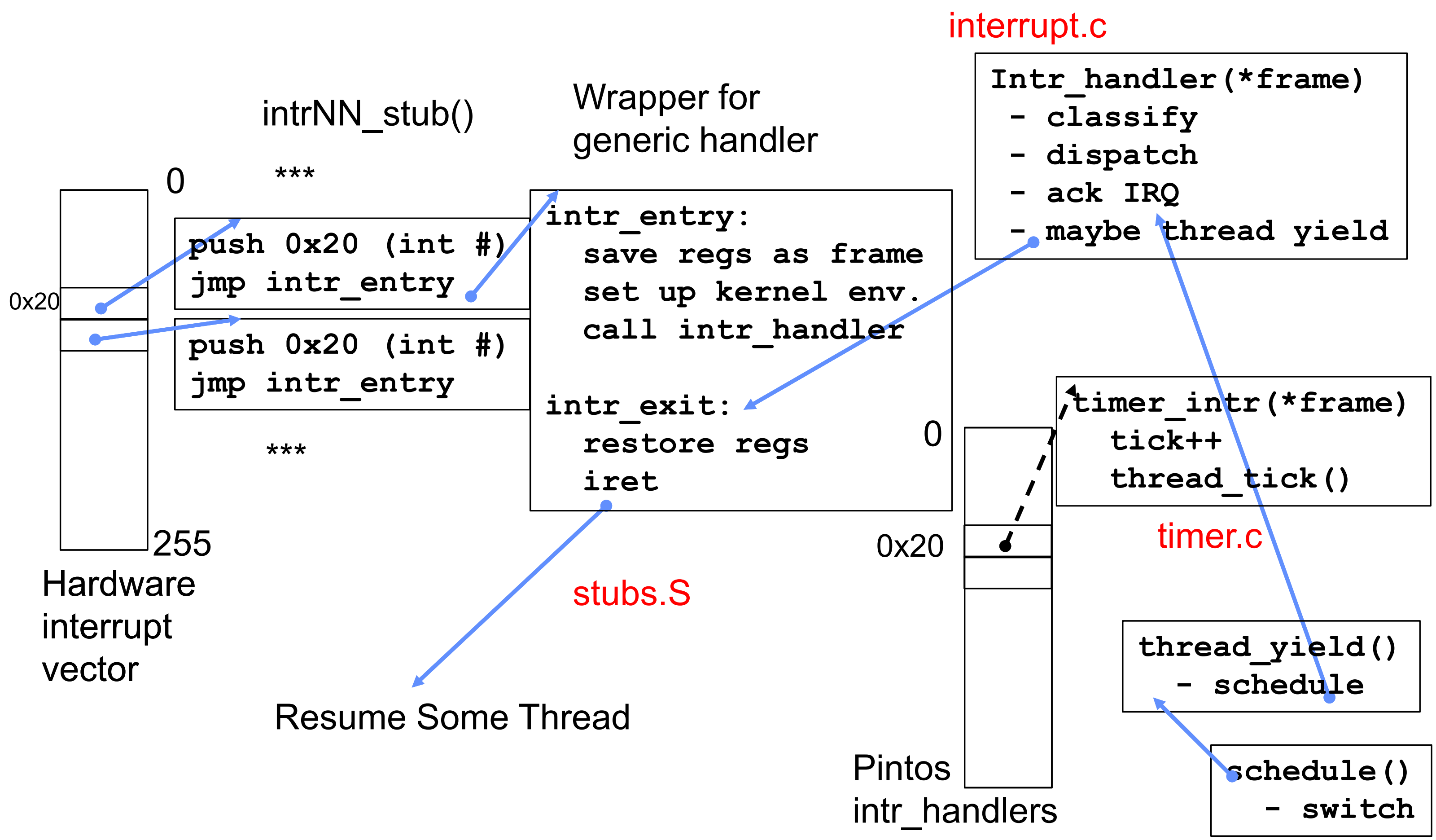
- thread_tick
  - Updates thread counters
  - If quanta exhausted, sets yield flag
- thread_yield
  - On path to rtn from interrupt
  - Sets current thread back to READY
  - Pushes it back on ready_list
  - Calls schedule to select next thread to run upon iret
- Schedule
  - Selects next thread to run
  - Calls switch_threads to change regs to point to stack for thread to resume
  - Sets its status to RUNNING
  - If user thread, activates the process
  - Returns back to intr_handler

Thread Switch (switch.S)

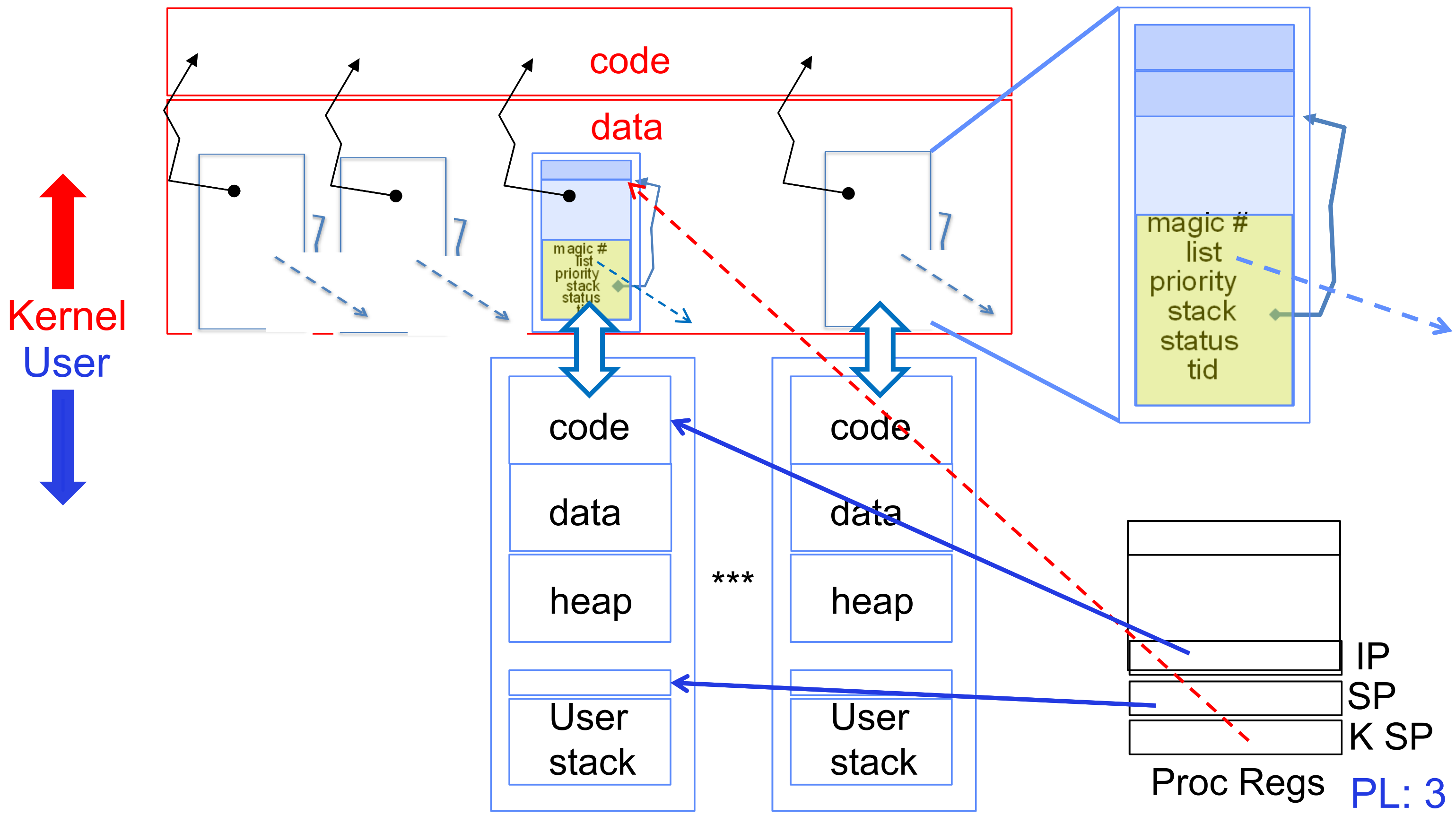


- switch_threads: save regs on current kernel stack, change SP, return from destination thread's call to switch_threads

Pintos Return from Processing for Timer (0x20)



Kernel → Different User Thread



- iret restores user stack and priority level (PL)

Famous Quote WRT Scheduling: Dennis Richie

Dennis Richie,
Unix V6, slp.c:

```
/*
 * If the new process paused because it was
 * swapped out, set the stack level to the last call
 * to savu(u_ssav).  This means that the return
 * which is executed immediately after the call to aretu
 * actually returns from the last routine which did
 * the savu.
 *
 * You are not expected to understand this.
 */
```

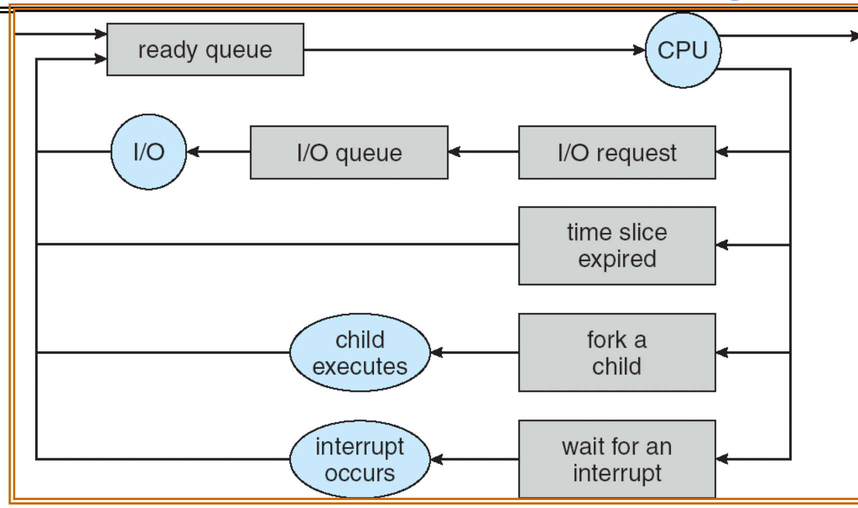
"If the new process paused because it was swapped out, set the stack level to the last call to savu(u_ssav). This means that the return which is executed immediately after the call to aretu actually returns from the last routine which did the savu."

"You are not expected to understand this."

Source: Dennis Ritchie, Unix V6 slp.c (context-switching code) as per The Unix Heritage Society(tuhs.org); gif by Eddie Koehler.

Included by Ali R. Butt in CS3204 from Virginia Tech

Recall: Scheduling



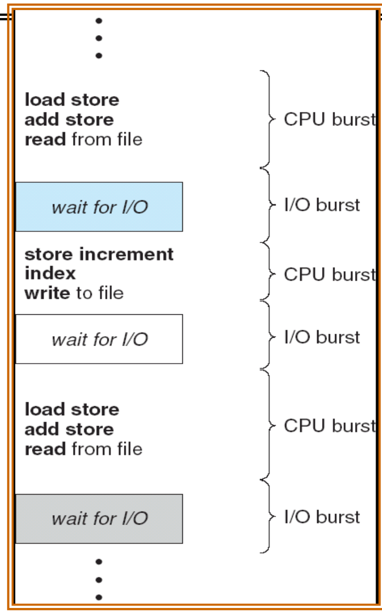
- Question: How is the OS to decide which of several tasks to take off a queue?
- Scheduling: deciding which threads are given access to resources from moment to moment
  – Often, we think in terms of CPU time, but could also think about access to resources like network BW or disk access

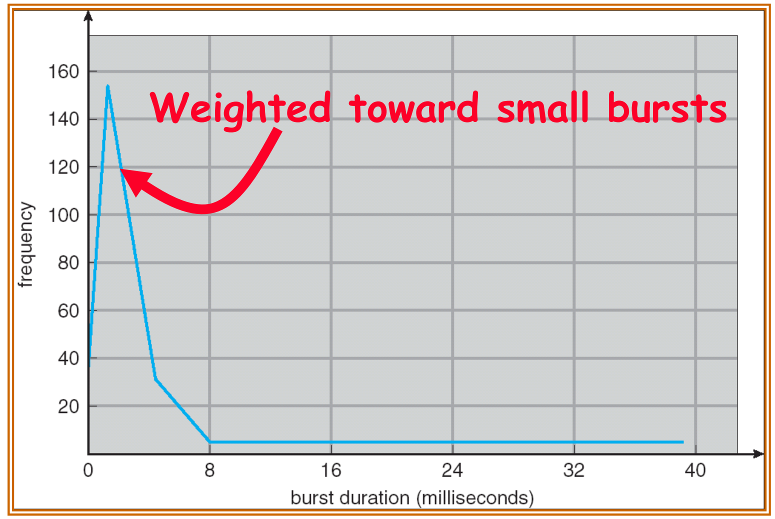
Scheduling: All About Queues

Scheduling Assumptions

- CPU scheduling big area of research in early 70's
- Many implicit assumptions for CPU scheduling:
  - One program per user
  - One thread per program
  - Programs are independent
- Clearly, these are unrealistic but they simplify the problem so it can be solved
  - For instance: is "fair" about fairness among users or programs?
    - » If I run one compilation job and you run five, you get five times as much CPU on many operating systems
- The high-level goal: Dole out CPU time to optimize some desired parameters of system

Assumption: CPU Bursts





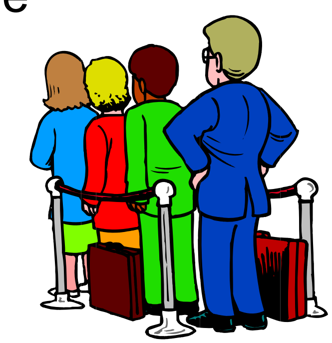
- Execution model: programs alternate between bursts of CPU and I/O
  - Program typically uses the CPU for some period of time, then does I/O, then uses CPU again
  - Each scheduling decision is about which job to give to the CPU for use by its next CPU burst
  - With timeslicing, thread may be forced to give up CPU before finishing current CPU burst

Scheduling Policy Goals/Criteria

- Minimize Response Time
  – Minimize elapsed time to do an operation (or job)
  – Response time is what the user sees:
    » Time to echo a keystroke in editor
    » Time to compile a program
    » Real-time Tasks: Must meet deadlines imposed by World
- Maximize Throughput
  – Maximize operations (or jobs) per second
  – Throughput related to response time, but not identical:
    » Minimizing response time will lead to more context switching than if you only maximized throughput
  – Two parts to maximizing throughput
    » Minimize overhead (for example, context-switching)
    » Efficient use of resources (CPU, disk, memory, etc)
- Fairness
  – Share CPU among users in some equitable way
  – Fairness is not minimizing average response time:
    » Better *average* response time by making system *less* fair

First-Come, First-Served (FCFS) Scheduling

- First-Come, First-Served (FCFS)
  - Also “First In, First Out” (FIFO) or “Run until done”
    - » In early systems, FCFS meant one program scheduled until done (including I/O)
    - » Now, means keep CPU until thread blocks



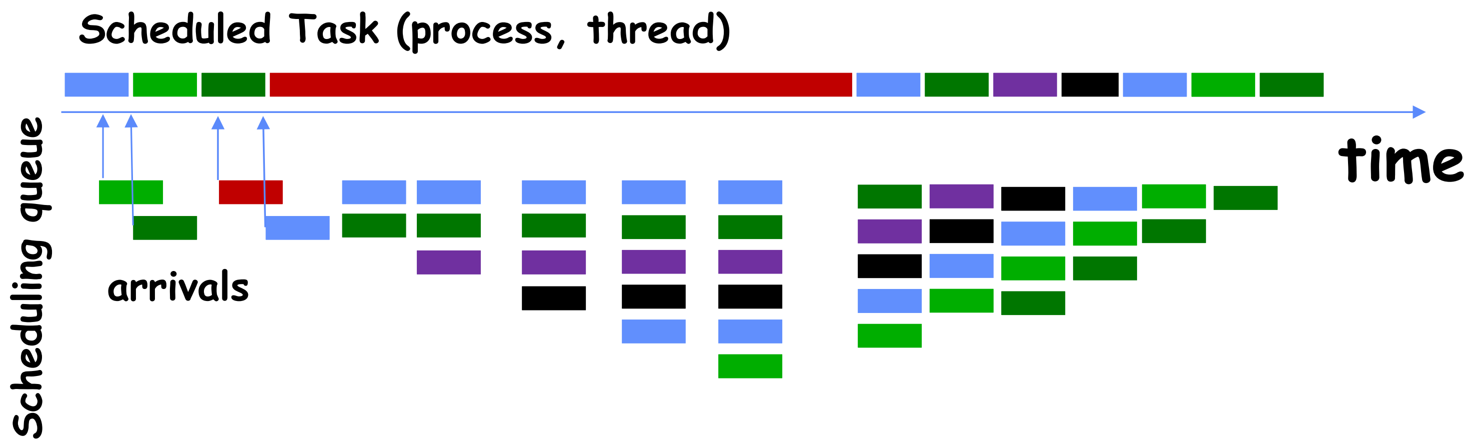
- Example:

Process	Burst Time
P_1	24
P_2	3
P_3	3

  - Suppose processes arrive in the order: P_1 , P_2 , P_3
    The Gantt Chart for the schedule is:

  - Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
  - Average waiting time: (0 + 24 + 27)/3 = 17
  - Average Completion time: (24 + 27 + 30)/3 = 27
- *Convoy effect:* short process stuck behind long process

Convoy effect



- With FCFS non-preemptive scheduling, convoys of small tasks tend to build up when a large one is running.

FCFS Scheduling (Cont.)

- Example continued:
  - Suppose that processes arrive in order: P2 , P3 , P1
    Now, the Gantt chart for the schedule is:

  - Waiting time for P1 = 6; P2 = 0; P3 = 3
  - Average waiting time: (6 + 0 + 3)/3 = 3
  - Average Completion time: (3 + 6 + 30)/3 = 13
- In second case:
  - Average waiting time is much better (before it was 17)
  - Average completion time is better (before it was 27)
- FIFO Pros and Cons:
  - Simple (+)
  - Short jobs get stuck behind long ones (-)
    - » Safeway: Getting milk, always stuck behind cart full of items!
      Upside: get to read about Space Aliens!

Administrivia

- Midterm I:
  - Grading done today by Tomorrow morning. Sorry for the delay!
  - Solutions will be up off the Resources page
- Project 1 final report is due Wednesday, February 28th
- Also due Wednesday: Peer evaluations
  - These are a required mechanism for evaluating group dynamics
  - Project scores are a zero-sum game
    - » In the normal/best case, all partners get the same grade
    - » In groups with issues, we may take points from non-participating group members and give them to participating group members!
- How does this work?
  - You get 20 points/partner to distribute as you want:
    Example—4 person group, you get 3 x 20 = 60 points
    - » If all your partners contributed equally, give the 20 points each
    - » Or, you could do something like:
      - 22 points partner 1
      - 22 points partner 2
      - 16 points partner 3
  - DO NOT GIVE YOURSELF POINTS!
    - » You are NOT an unbiased evaluator of your group behavior

Round Robin (RR) Scheduling

- FCFS Scheme: Potentially bad for short jobs!
  - Depends on submit order
  - If you are first in line at supermarket with milk, you don't care who is behind you, on the other hand…
- Round Robin Scheme: Preemption!
  
  - Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds
  - After quantum expires, the process is preempted and added to the end of the ready queue.
  - n processes in ready queue and time quantum is $q \Rightarrow$
    - » Each process gets $1/n$ of the CPU time
    - » In chunks of at most q time units
    - » No process waits more than $(n-1)q$ time units

RR Scheduling (Cont.)

- Performance
  - *q* large ⇒ FCFS
  - *q* small ⇒ Interleaved (really small ⇒ hyperthreading?)
  - *q* must be large with respect to context switch, otherwise overhead is too high (all overhead)

Example of RR with Time Quantum = 20

- Example:

Process	Burst Time
P_1	53
P_2	8
P_3	68
P_4	24

  – The Gantt chart is:

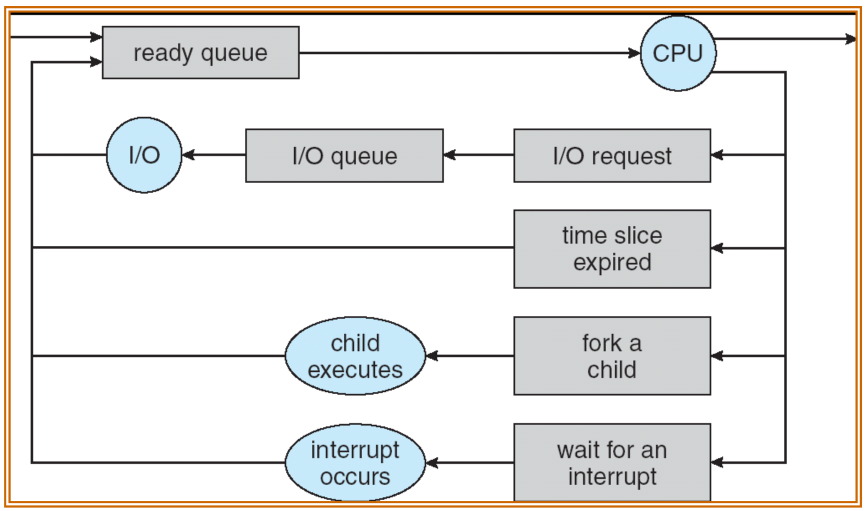
P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_3

0 20 28 48 68 88 108 112 125 145 153

  – Waiting time for
    P_1=(68-20)+(112-88)=72
    P_2=(20-0)=20
    P_3=(28-0)+(88-48)+(125-108)=85
    P_4=(48-0)+(108-68)=88
  – Average waiting time = (72+20+85+88)/4=66¼
  – Average completion time = (125+28+153+112)/4 = 104½
- Thus, Round-Robin Pros and Cons:
  – Better for short jobs, Fair (+)
  – Context-switching time adds up for long jobs (-)

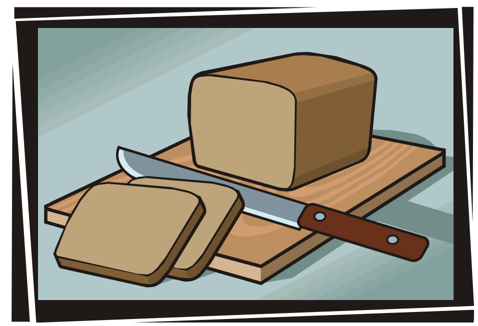
How to Implement RR in the Kernel?

- FIFO Queue, as in FCFS
- But preempt job after quantum expires, and send it to the back of the queue
  – How? Timer interrupt!
  – And, of course, careful synchronization



Round-Robin Discussion

- How do you choose time slice?
  - What if too big?
    - » Response time suffers
  - What if infinite (∞)?
    - » Get back FIFO
  - What if time slice too small?
    - » Throughput suffers!



- Actual choices of timeslice:
  - Initially, UNIX timeslice one second:
    - » Worked ok when UNIX was used by one or two people.
    - » What if three compilations going on? 3 seconds to echo each keystroke!
  - Need to balance short-job performance and long-job throughput:
    - » Typical time slice today is between 10ms – 100ms
    - » Typical context-switching overhead is 0.1ms – 1ms
    - » Roughly 1% overhead due to context-switching

Comparisons between FCFS and Round Robin

- Assuming zero-cost context-switching time, is RR always better than FCFS?
- Simple example: 10 jobs, each take 100s of CPU time
  RR scheduler quantum of 1s
  All jobs start at the same time
- Completion Times:

Job #	FIFO	RR
1	100	991
2	200	992
…	…	…
9	900	999
10	1000	1000

  – Both RR and FCFS finish at the same time
  – Average completion time is much worse under RR!
    » Bad when all jobs same length
- Also: Cache state must be shared between all jobs with RR but can be devoted to each job with FIFO
  – Total time for RR longer even for zero-cost switch!

Earlier Example with Different Time Quantum

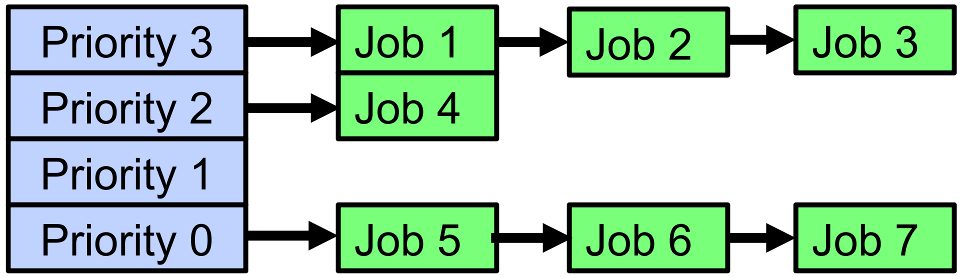
Best FCFS:

P$_2$ [8]	P$_4$ [24]	P$_1$ [53]	P$_3$ [68]

0 8 32 85 153

	Quantum	P$_1$	P$_2$	P$_3$	P$_4$	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	61¼
	Q = 8	80	8	85	56	57¼
	Q = 10	82	10	85	68	61¼
	Q = 20	72	20	85	88	66¼
	Worst FCFS	68	145	0	121	83½
Completion Time	Best FCFS	85	8	153	32	69½
	Q = 1	137	30	153	81	100½
	Q = 5	135	28	153	82	99½
	Q = 8	133	16	153	80	95½
	Q = 10	135	18	153	92	99½
	Q = 20	125	28	153	112	104½
	Worst FCFS	121	153	68	145	121¾

Handling Differences in Importance: Strict Priority Scheduling



- Execution Plan
  - Always execute highest-priority runable jobs to completion
  - Each queue can be processed in RR with some time-quantum
- Problems:
  - Starvation:
    - » Lower priority jobs don't get to run because higher priority jobs
  - Deadlock: Priority Inversion
    - » Happens when low priority task has lock needed by high-priority task
    - » Usually involves third, intermediate priority task preventing high-priority task from running
- How to fix problems?
  - Dynamic priorities – adjust base-level priority up or down based on heuristics about interactivity, locking, burst behavior, etc…

Scheduling Fairness

- What about fairness?
  - Strict fixed-priority scheduling between queues is unfair (run highest, then next, etc):
    - » long running jobs may never get CPU
    - » Urban legend: In Multics, shut down machine, found 10-year-old job $\Rightarrow$ Ok, probably not…
  - Must give long-running jobs a fraction of the CPU even when there are shorter jobs to run
  - Tradeoff: fairness gained by hurting avg response time!

Scheduling Fairness

- How to implement fairness?
  - Could give each queue some fraction of the CPU
    - » What if one long-running job and 100 short-running ones?
    - » Like express lanes in a supermarket—sometimes express lanes get so long, get better service by going into one of the other lines
  - Could increase priority of jobs that don't get service
    - » What is done in some variants of UNIX
    - » This is ad hoc—what rate should you increase priorities?
    - » And, as system gets overloaded, no job gets CPU time, so everyone increases in priority⇒Interactive jobs suffer

What if we Knew the Future?

- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  - Run whatever job has least amount of computation to do
  - Sometimes called “Shortest Time to Completion First” (STCF)

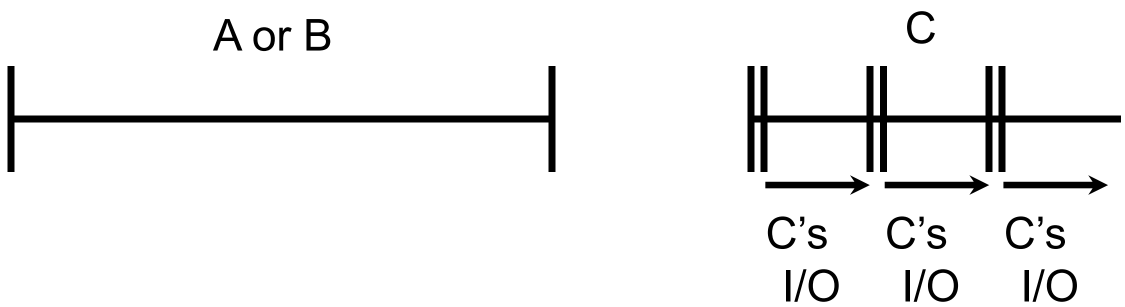
- Shortest Remaining Time First (SRTF):
  - Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
  - Sometimes called “Shortest Remaining Time to Completion First” (SRTCF)
- These can be applied to whole program or current CPU burst
  - Idea is to get short jobs out of the system
  - Big effect on short jobs, only small effect on long ones
  - Result is better average response time

Discussion

- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - Since SRTF is always at least as good as SJF, focus on SRTF

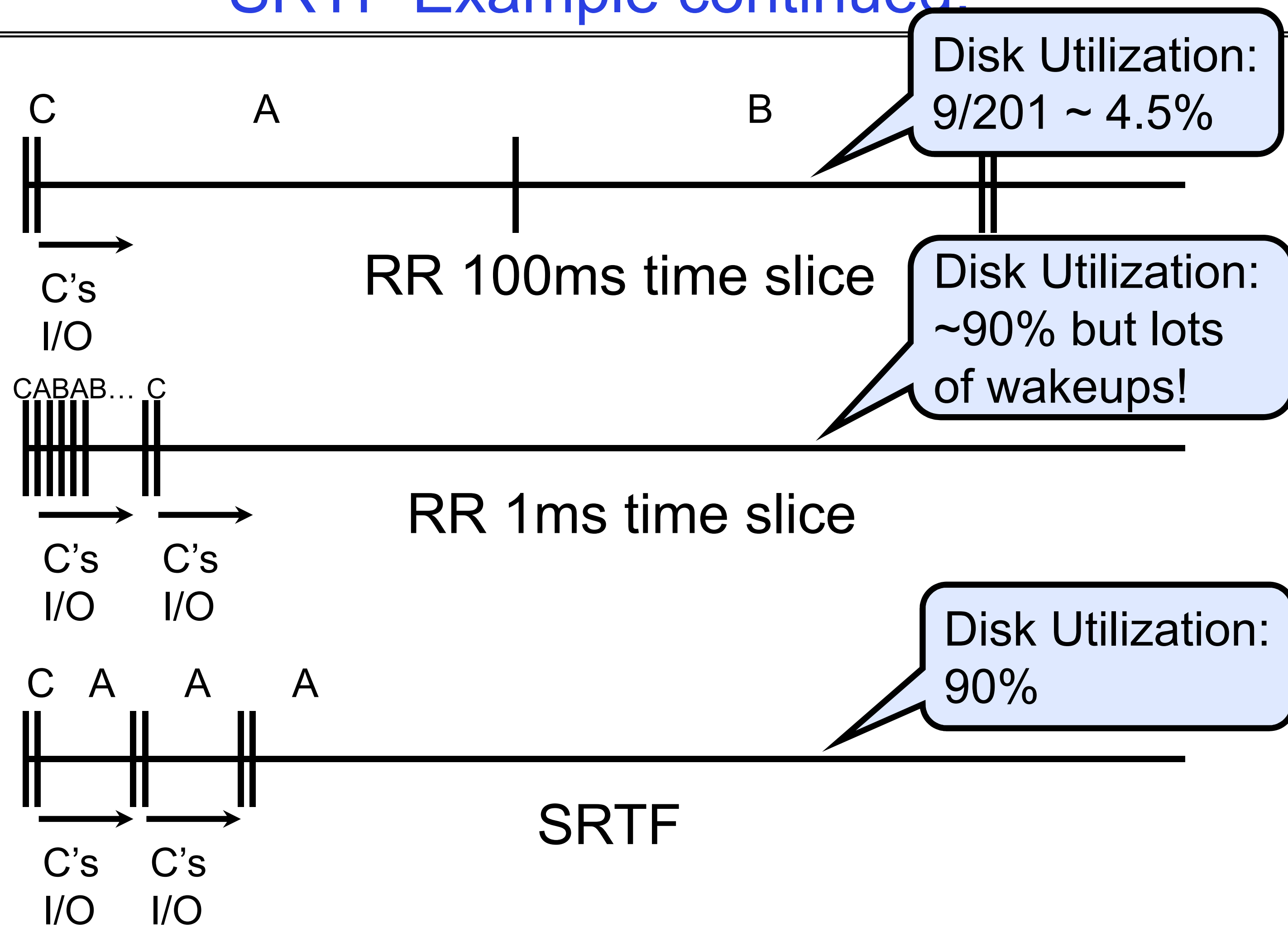
- Comparison of SRTF with FCFS
  - What if all jobs the same length?
    - » SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
  - What if jobs have varying length?
    - » SRTF: short jobs not stuck behind long ones

Example to illustrate benefits of SRTF



- Three jobs:
  - A, B: both CPU bound, run for week
    C: I/O bound, loop 1ms CPU, 9ms disk I/O
  - If only one at a time, C uses 90% of the disk, A or B could use 100% of the CPU
- With FCFS:
  - Once A or B get in, keep CPU for two weeks
- What about RR or SRTF?
  - Easier to see with a timeline

SRTF Example continued:

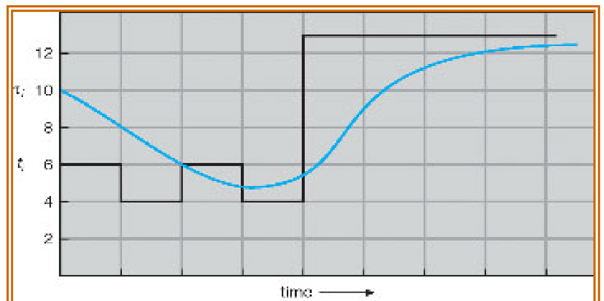


SRTF Further discussion

- Starvation
  - SRTF can lead to starvation if many small jobs!
  - Large jobs never get to run
- Somehow need to predict future
  - How can we do this?
  - Some systems ask the user
    - When you submit a job, have to say how long it will take
    - To stop cheating, system kills job if takes too long
  - But: hard to predict job's runtime even for non-malicious users
- Bottom line, can't really know how long job will take
  - However, can use SRTF as a yardstick for measuring other policies
  - Optimal, so can't do any better
- SRTF Pros & Cons
  - Optimal (average response time) (+)
  - Hard to predict future (-)
  - Unfair (-)

Predicting the Length of the Next CPU Burst

- Adaptive: Changing policy based on past behavior
  – CPU scheduling, in virtual memory, in file systems, etc
  – Works because programs have predictable behavior
    » If program was I/O bound in past, likely in future
    » If computer behavior were random, wouldn't help
- Example: SRTF with estimated burst length
  – Use an estimator function on previous bursts:
  Let t_{n-1}, t_{n-2}, t_{n-3}, etc. be previous CPU burst lengths.
  Estimate next burst $\tau_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \ldots)$
  – Function f could be one of many different time series estimation schemes (Kalman filters, etc)
  – For instance, exponential averaging
  $\tau n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$
  with $(0<\alpha\leq1)$



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

Lottery Scheduling

- Yet another alternative: Lottery Scheduling
  - Give each job some number of lottery tickets
  - On each time slice, randomly pick a winning ticket
  - On average, CPU time is proportional to number of tickets given to each job
- How to assign tickets?
  - To approximate SRTF, short running jobs get more, long running jobs get fewer
  - To avoid starvation, every job gets at least one ticket (everyone makes progress)
- Advantage over strict priority scheduling: behaves gracefully as load changes
  - Adding or deleting a job affects all jobs proportionally, independent of how many tickets each job possesses

Lottery Scheduling Example (Cont.)

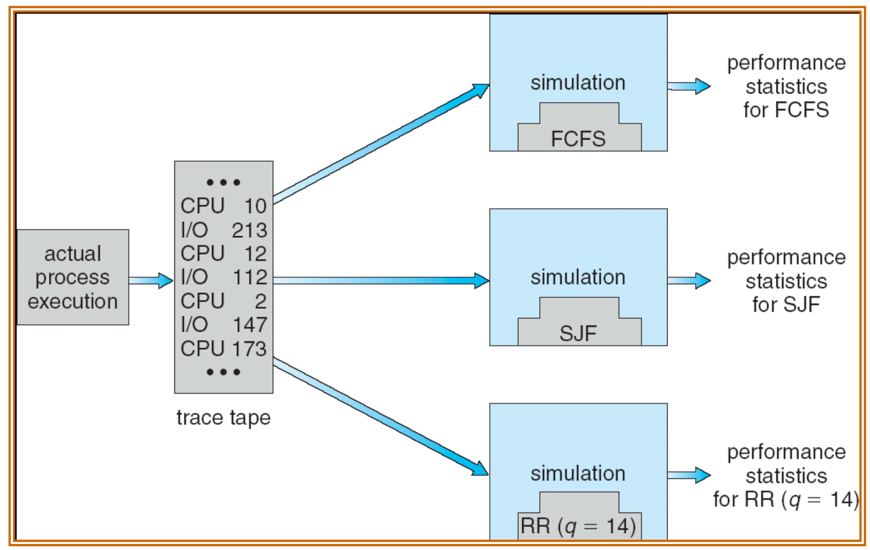
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# short jobs/ # long jobs	% of CPU each short jobs gets	% of CPU each long jobs gets
1/1	91%	9%
0/2	N/A	50%
2/0	50%	N/A
10/1	9.9%	0.99%
1/10	50%	5%

  - What if too many short jobs to give reasonable response time?
    - » If load average is 100, hard to make progress
    - » One approach: log some user out

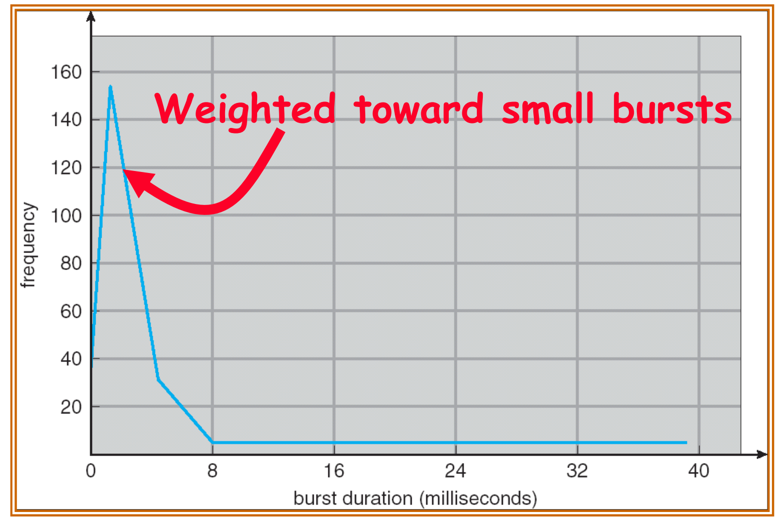
How to Evaluate a Scheduling algorithm?

- Deterministic modeling
  - takes a predetermined workload and compute the performance of each algorithm for that workload
- Queueing models
  - Mathematical approach for handling stochastic workloads
- Implementation/Simulation:
  - Build system which allows actual algorithms to be run against actual data
  - Most flexible/general

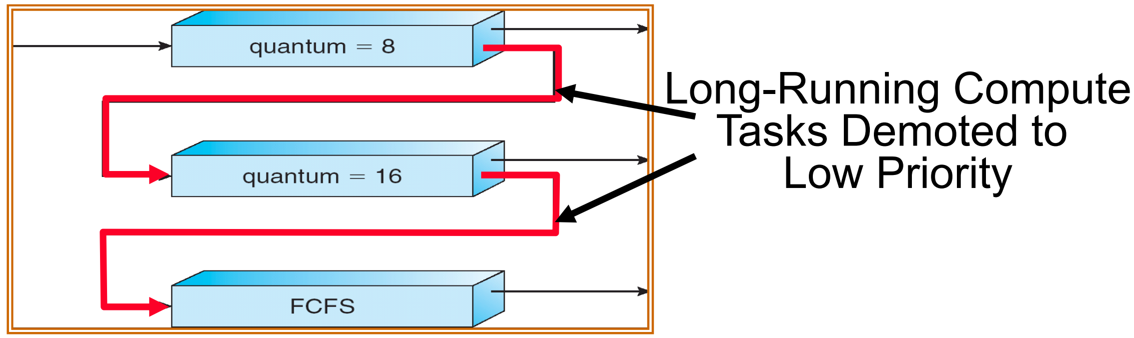


How to Handle Simultaneous Mix of Diff Types of Apps?

- Consider mix of interactive and high throughput apps:
  - How to best schedule them?
  - How to recognize one from the other?
    - » Do you trust app to say that it is "interactive"?
  - Should you schedule the set of apps identically on servers, workstations, pads, and cellphones?
- For instance, is Burst Time (observed) useful to decide which application gets CPU time?
  - Short Bursts ⇒ Interactivity ⇒ High Priority?
- Assumptions encoded into many schedulers:
  - Apps that sleep a lot and have short bursts must be interactive apps – they should get high priority
  - Apps that compute a lot should get low(er?) priority, since they won't notice intermittent bursts from interactive apps
- Hard to characterize apps:
  - What about apps that sleep for a long time, but then compute for a long time?
  - Or, what about apps that must run under all circumstances (say periodically)

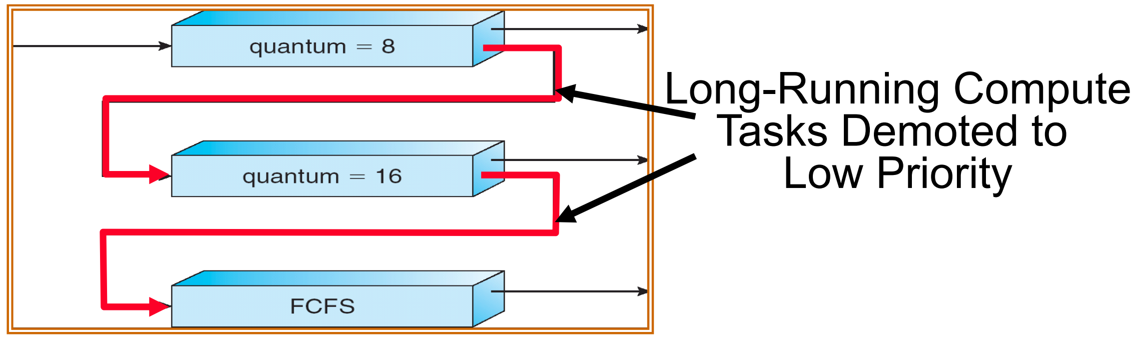


Multi-Level Feedback Scheduling



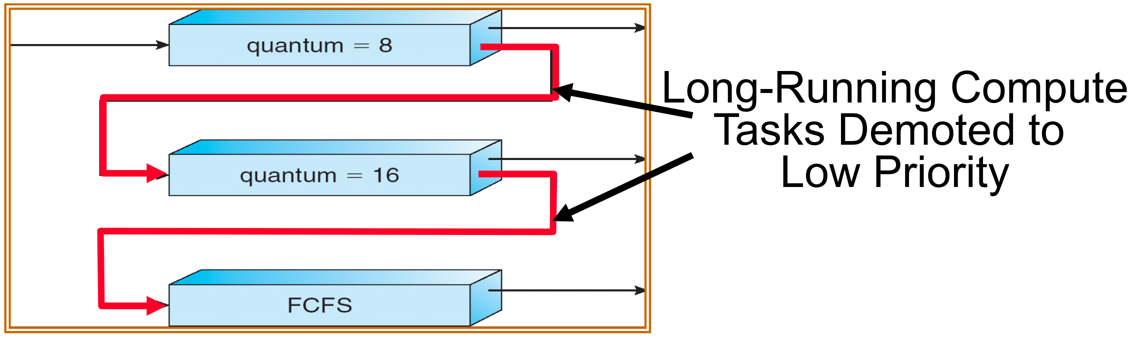
- Another method for exploiting past behavior (first use in CTSS)
  - Multiple queues, each with different priority
    - » Higher priority queues often considered “foreground” tasks
  - Each queue has its own scheduling algorithm
    - » e.g. foreground – RR, background – FCFS
    - » Sometimes multiple RR priorities with quantum increasing exponentially (highest:1ms, next: 2ms, next: 4ms, etc)
- Adjust each job’s priority as follows (details vary)
  - Job starts in highest priority queue
  - If timeout expires, drop one level
  - If timeout doesn’t expire, push up one level (or to top)

Scheduling Details



- Result approximates SRTF:
  - CPU bound jobs drop like a rock
  - Short-running I/O bound jobs stay near top
- Scheduling must be done between the queues
  - Fixed priority scheduling:
    - » serve all from highest priority, then next priority, etc.
  - Time slice:
    - » each queue gets a certain amount of CPU time
    - » e.g., 70% to highest, 20% next, 10% lowest

Scheduling Details



- Countermeasure: user action that can foil intent of the OS designers
  – For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
  – Of course, if everyone did this, wouldn't work!
- Example of Othello program:
  – Playing against competitor, so key was to do computing at higher priority the competitors.
    » Put in printf's, ran much faster!

Case Study: Linux O(1) Scheduler

- Priority-based scheduler: 140 priorities
  - 40 for “user tasks” (set by “nice”), 100 for “Realtime/Kernel”
  - Lower priority value ⇒ higher priority (for realtime values)
  - Highest priority value ⇒ Lower priority (for nice values)
  - All algorithms O(1)
    - » Timeslices/priorities/interactivity credits all computed when job finishes time slice
    - » 140-bit bit mask indicates presence or absence of job at given priority level
- Two separate priority queues: “active” and “expired”
  - All tasks in the active queue use up their timeslices and get placed on the expired queue, after which queues swapped
- Timeslice depends on priority – linearly mapped onto timeslice range
  - Like a multi-level queue (one queue per priority) with different timeslice at each level
  - Execution split into “Timeslice Granularity” chunks – round robin through priority

O(1) Scheduler Continued

- Heuristics
  - User-task priority adjusted ±5 based on heuristics
    - » p->sleep_avg = sleep_time – run_time
    - » Higher sleep_avg ⇒ more I/O bound the task, more reward (and vice versa)
  - Interactive Credit
    - » Earned when a task sleeps for a “long” time
    - » Spend when a task runs for a “long” time
    - » IC is used to provide hysteresis to avoid changing interactivity for temporary changes in behavior
  - However, “interactive tasks” get special dispensation
    - » To try to maintain interactivity
    - » Placed back into active queue, unless some other task has been starved for too long…
- Real-Time Tasks
  - Always preempt non-RT tasks
  - No dynamic adjustment of priorities
  - Scheduling schemes:
    - » SCHED_FIFO: preempts other tasks, no timeslice limit
    - » SCHED_RR: preempts normal tasks, RR scheduling amongst tasks of same priority

So, Does the OS Schedule Processes or Threads?

- Many textbooks use the “old model”—one thread per process
- Usually it's really: **threads** (e.g., in Linux)

- One point to notice: switching threads vs. switching processes incurs different costs:
  - Switch threads: Save/restore registers
  - Switch processes: Change active address space too!
    - » Expensive
    - » Disrupts caching

- Recall, However: Simultaneous Multithreading (or “Hyperthreading”)
  - Different threads interleaved on a cycle-by-cycle basis and can be in different processes (have different address spaces)

Multi-Core Scheduling

- Algorithmically, not a huge difference from single-core scheduling

- Implementation-wise, helpful to have *per-core* scheduling data structures
  - Cache coherence

- *Affinity scheduling*: once a thread is scheduled on a CPU, OS tries to reschedule it on the same CPU
  - Cache reuse

Recall: *Spinlocks for multiprocessing*

- Spinlock implementation:

```
int value = 0; // Free
Acquire() {
   while (test&set(&value)) {}; // spin while busy
}
Release() {
   value = 0;                    // atomic store
}
```

- Spinlock doesn't put the calling thread to sleep—it just busy waits
  - When might this be preferable?
    - » Waiting for limited number of threads at a barrier in a multiprocessing (multicore) program
    - » Wait time at barrier would be greatly increased if threads must be woken inside kernel
- Every `test&set()` is a write, which makes value ping-pong around between core-local caches (using lots of memory!)
  - So – really want to use `test&test&set()` !
- As we discussed in Lecture 8, the extra read eliminates the ping-ponging issues:

```
// Implementation of test&test&set():
Acquire() {
   do {
      while(value);            // wait until might be free
   } while (test&set(&value)); // exit if acquire lock
}
```

Gang Scheduling and Parallel Applications

- When multiple threads work together on a multi-core system, try to schedule them together
  - Makes spin-waiting more efficient (inefficient to spin-wait for a thread that's suspended)

- Alternative: OS informs a parallel program how many processors its threads are scheduled on (*Scheduler Activations*)
  - Application adapts to number of cores that it has scheduled
  - "Space sharing" with other parallel programs can be more efficient, because parallel speedup is often sublinear with the number of cores

Conclusion

- Scheduling Goals:
  - Minimize Response Time (e.g. for human interaction)
  - Maximize Throughput (e.g. for large computations)
  - Fairness (e.g. Proper Sharing of Resources)
  - Predictability (e.g. Hard/Soft Realtime)
- Round-Robin Scheduling:
  - Give each thread a small amount of CPU time when it executes; cycle between all ready threads
  - Pros: Better for short jobs
- Shortest Job First (SJF)/Shortest Remaining Time First (SRTF):
  - Run whatever job has the least amount of computation to do/least remaining amount of computation to do
- Multi-Level Feedback Scheduling:
  - Multiple queues of different priorities and scheduling algorithms
  - Automatic promotion/demotion of process priority in order to approximate SJF/SRTF