ICS143A: Principles of Operating Systems

Lecture 18: Process scheduling

This lecture is heavily based on
the material developed by Don Porter

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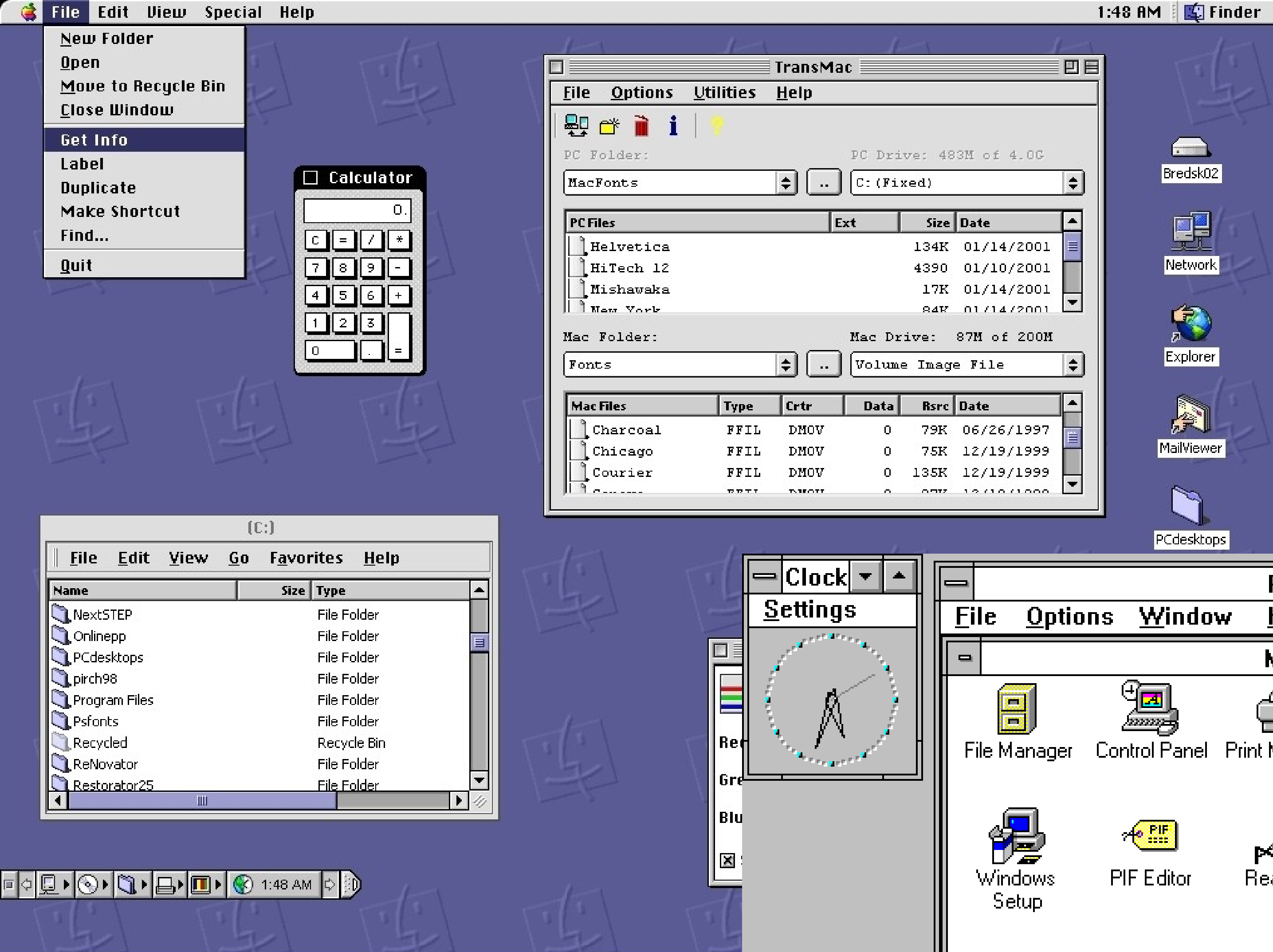
Cooperative vs preemptive

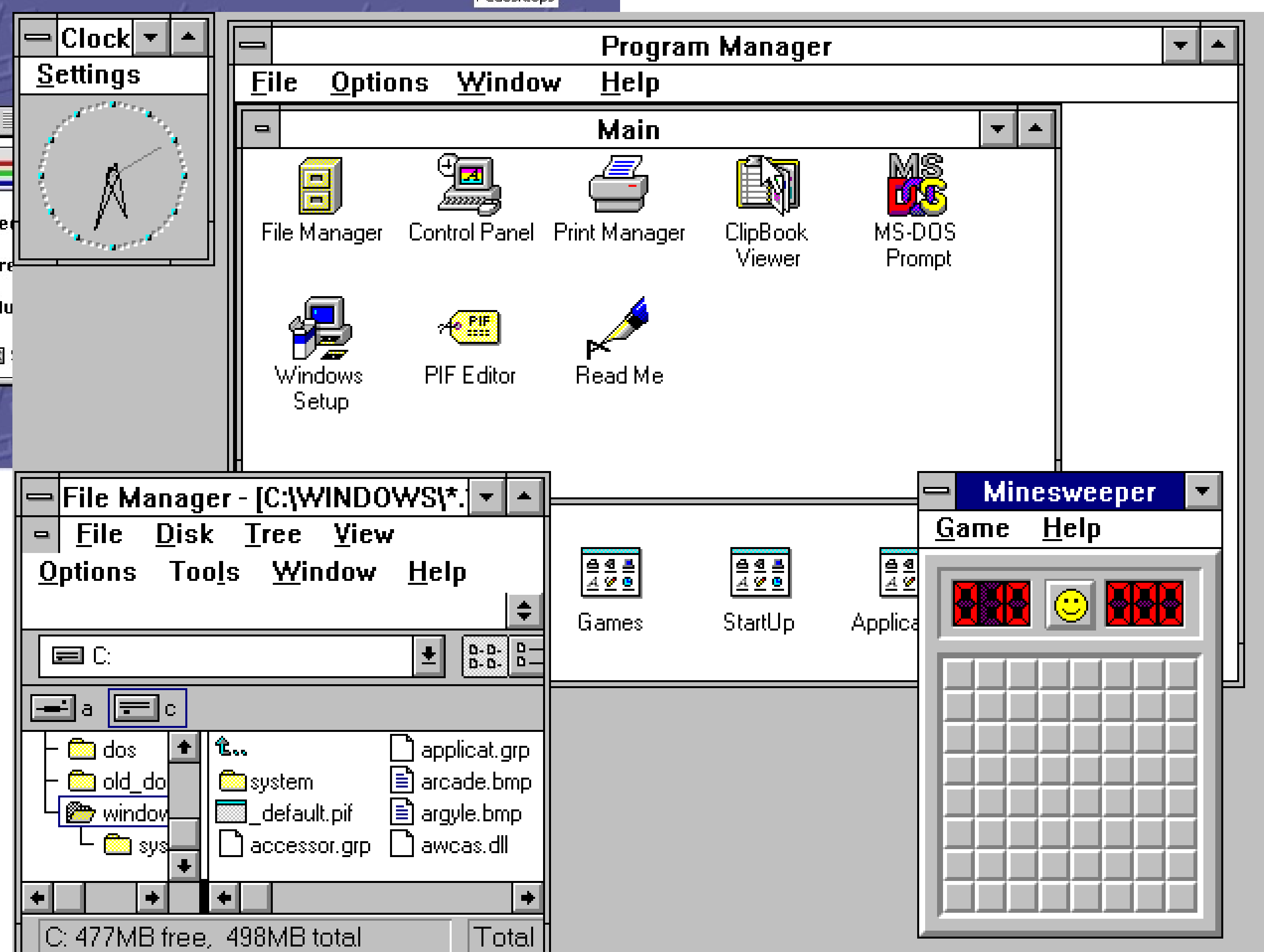
- What is cooperative multitasking?
- What is preemptive multitasking?
- Pros/cons?

Cooperative vs preemptive

- What is cooperative multitasking?
  - Processes voluntarily yield CPU when they are done
- What is preemptive multitasking?
  - OS only lets tasks run for a limited time, then forcibly context switches the CPU
- Pros/cons?
  - Cooperative gives more control; so much that one task can hog the CPU forever
  - Preemptive gives OS more control, more overheads/complexity



- MacOS 9



- Windows 3.1

At what point process can get preempted?

At what point process can get preempted?

- When entered the kernel
  - Inside one of the system calls
- Timer interrupt
  - Ensures maximum time slice

Policy vs mechanism

- Remember we know the mechanism
  - Context switching
    - Switch stacks
- This lecture is about policy
  - Pick the next process to run

Policy goals

- Fairness
  - Everything gets a fair share of the CPU
- Real-time deadlines
  - CPU time before a deadline more valuable than time after
- Latency vs. throughput: Timeslice length matters!
  - GUI programs should feel responsive
  - CPU-bound jobs want long timeslices, better throughput
- User priorities
  - Virus scanning is nice, but I don’t want it slowing things down

Strawman scheduler (xv6)

- Organize all processes as a simple list
- In schedule():
  - Pick first one on list to run next
  - Put suspended task at the end of the list

Xv6 scheduler

```
2458 scheduler(void)
2459 {
2462   for(;;){
2468     for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
2469       if(p->state != RUNNABLE)
2470         continue;
2475       proc = p;
2476       switchuvm(p);
2477       p->state = RUNNING;
2478       swtch(&cpu->scheduler, proc->context);
2479       switchkvm();
2483       proc = 0;
2484     }
2487   }
2488 }
```

Strawman scheduler (xv6)

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- Problem?

Strawman scheduler

- Organize all processes as a simple list
- In schedule():
  - Pick first one on list to run next
  - Put suspended task at the end of the list
- Problem?
  - Allows only round-robin scheduling
  - Can’t prioritize tasks

Priority based scheduling

- Higher-priority processes run first
- Processes within the same priority are round-robin

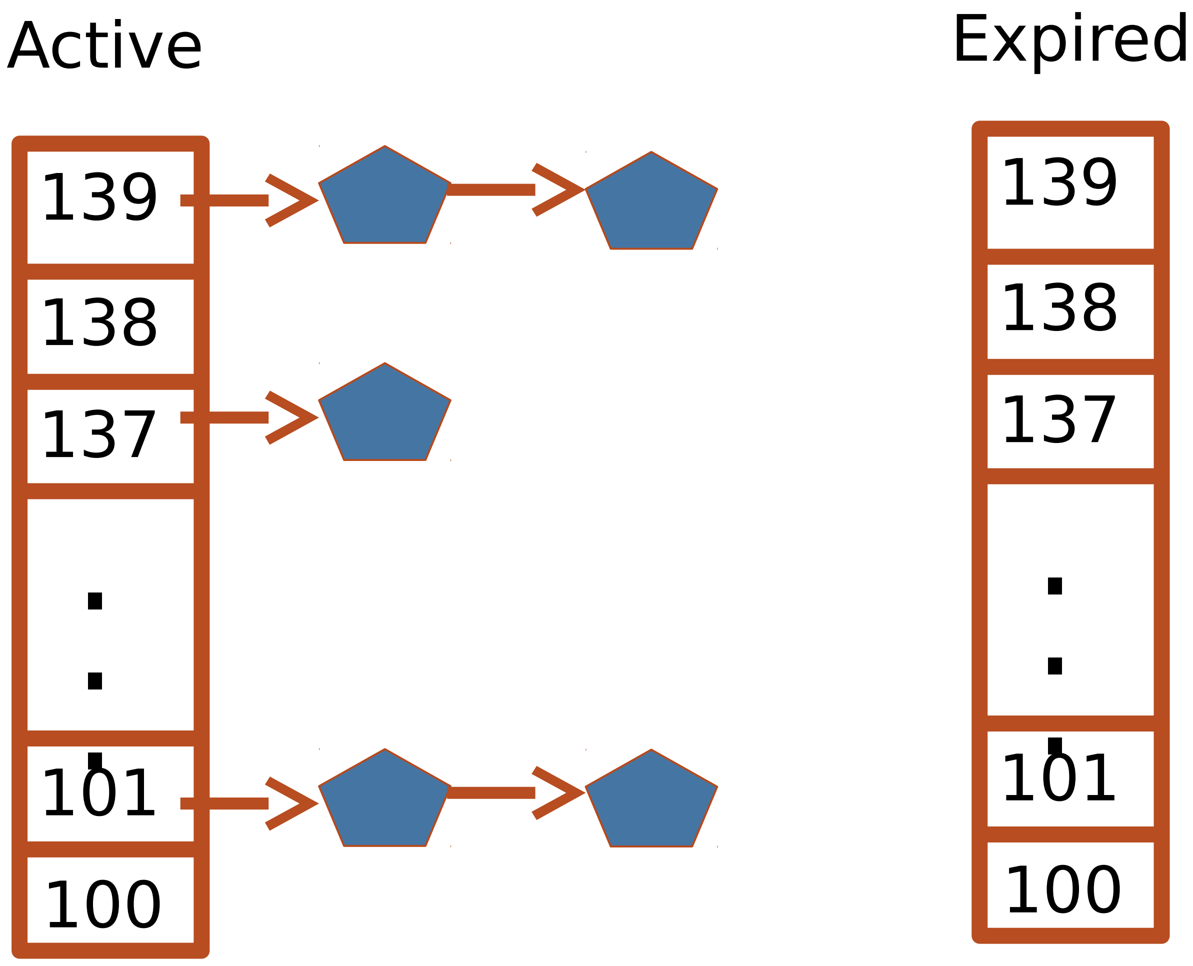
O(1) scheduler (Linux 2.6 – 2.6.22)

- Priority based scheduling
- Goal: decide who to run next, independent of number of processes in system
  - Still maintain ability to prioritize tasks, handle partially unused quanta, etc

O(1) data structures

- runqueue: a list of runnable processes
  - Blocked processes are not on any runqueue
  - A runqueue belongs to a specific CPU
  - Each task is on exactly one runqueue
  - Task only scheduled on runqueue's CPU unless migrated
- 2 *40 * #CPUs runqueues
  - 40 dynamic priority levels (more later)
  - 2 sets of runqueues – one active and one expired

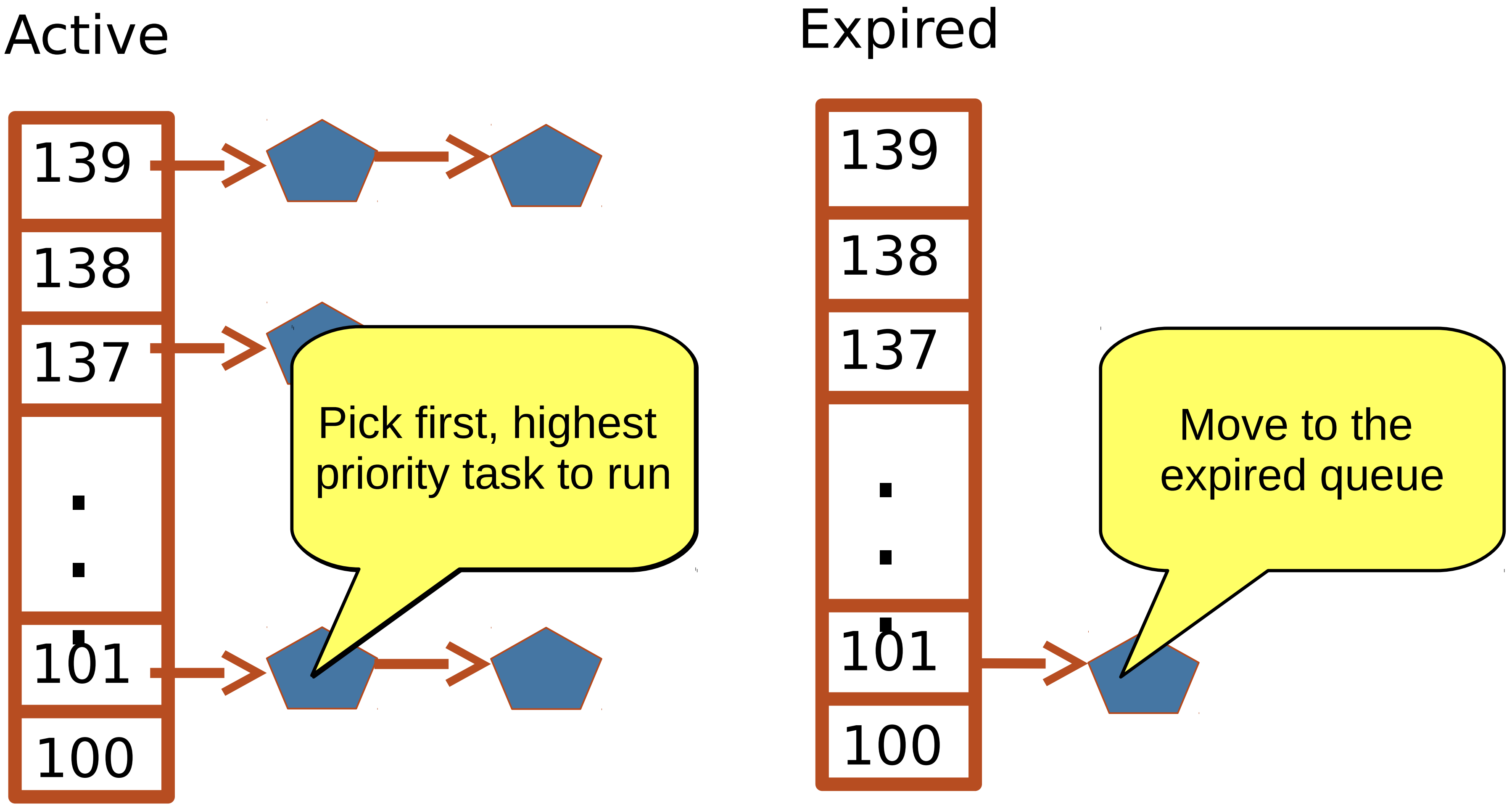
O(1) data structures (contd)



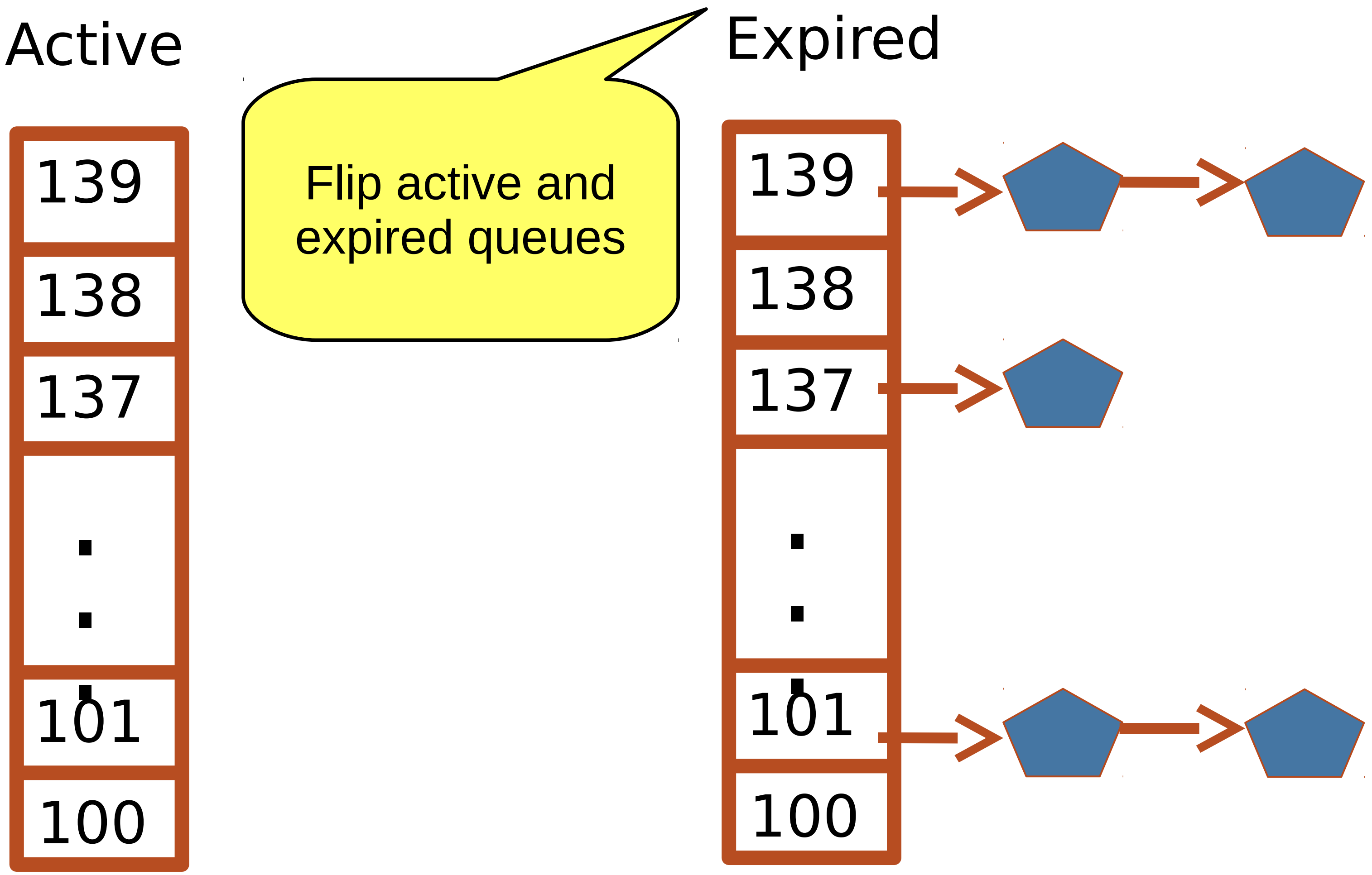
O(1) intuition

- Take the first task off the lowest-numbered runqueue on active set
  - Confusingly: a lower priority value means higher priority
- When done, put it on appropriate runqueue on expired set
- Once active is completely empty, swap which set of runqueues is active and expired
- Constant time, since fixed number of queues to check; only take first item from non-empty queue

O(1) example


Active
139
138
137
101
100
Pick first, highest priority task to run
Expired
139
138
137
101
100
Move to the expired queue

What now?

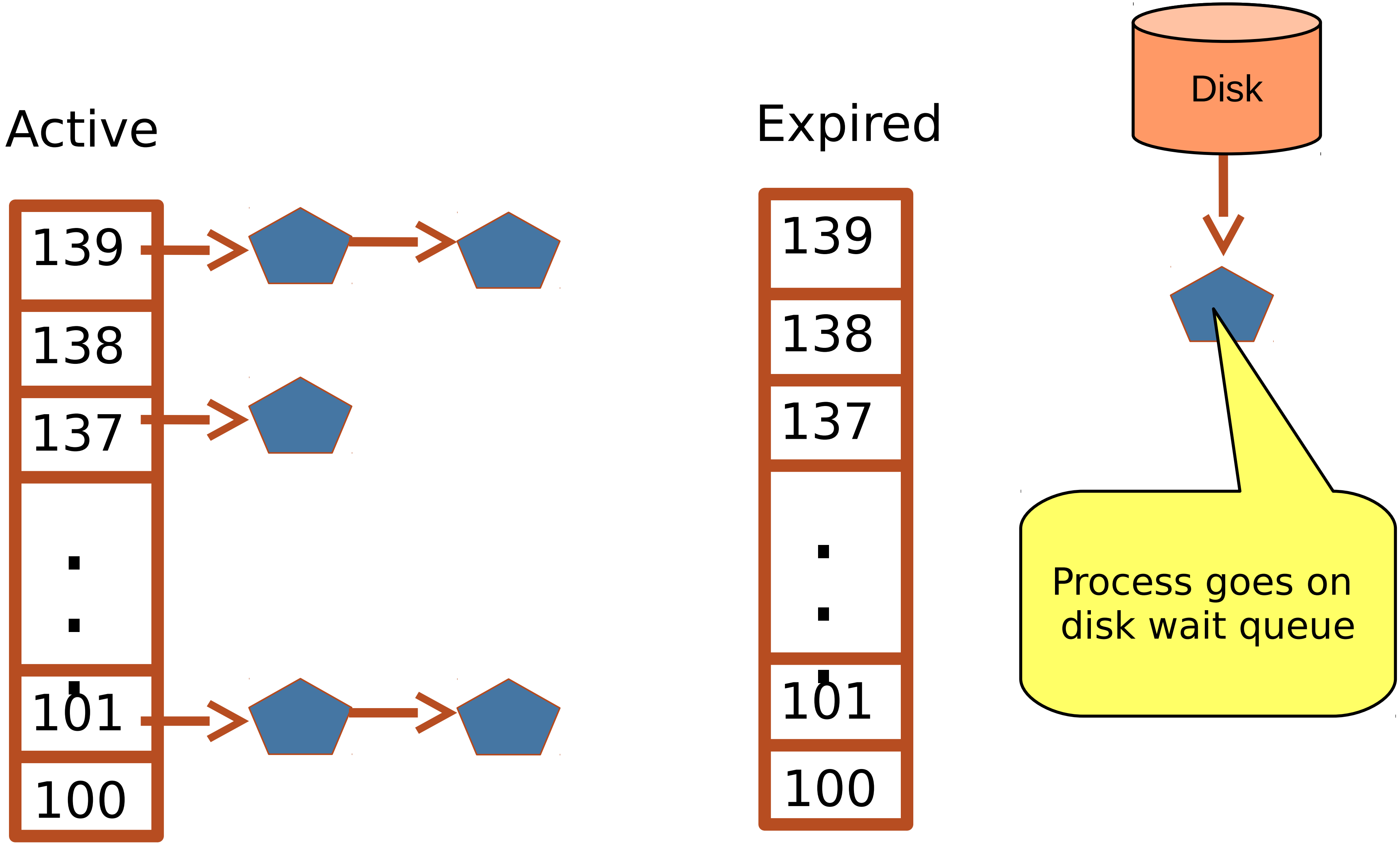


Active
Flip active and expired queues
Expired
139
138
137
101
100
139
138
137
101
100

Blocked tasks

- What if a program blocks on I/O, say for the disk?
  - It still has part of its quantum left
  - Not runnable, so don’t waste time putting it on the active or expired runqueues
- We need a “wait queue” associated with each blockable event
  - Disk, lock, pipe, network socket, etc.

Blocking example



Blocked tasks (contd)

- A blocked task is moved to a wait queue until the expected event happens
  - **No longer on any active or expired queue!**
- Disk example:
  - After I/O completes, interrupt handler moves task back to active runqueue

Time slice tracking

- Each task tracks ticks left in ‘time_slice’ field
  - On each clock tick: `current->time_slice--`
  - If time slice goes to zero, move to expired queue
  - Refill time slice
  - Schedule someone else
  - An unblocked task can use balance of time slice
  - Forking halves time slice with child

More on priorities

- 100 = highest priority
  - Priorities 0 – 99 are for real-time processes
- 139 = lowest priority
- 120 = base priority
  - “nice” value: user-specified adjustment to base priority
  - Selfish (not nice) = -20 (I want to go first)
  - Really nice = +19 (I will go last)

Base time slice

- Timeslice:

  If priority < 120

    Time = (140 – prio) * 20 ms

  else

    Time = (140 – prio) * 5 ms

- “Higher” priority tasks get more time
  - And run first

Responsive UI

- Most GUI programs are I/O bound
  - Wait on the user
  - Unlikely to use entire time slice
- Users get annoyed when they type a key and it takes a long time to appear
- Idea: give UI programs a priority boost
  - Go to front of line, run briefly, block on I/O again
- Which ones are the UI programs?

Idea: infer from sleep time

- By definition, I/O bound applications spend most of their time waiting on I/O
- We can monitor I/O wait time and infer which programs are GUI (and disk intensive)
- Give these applications a priority boost
- Note that this behavior can be dynamic
  - Ex: GUI configures DVD ripping (I/O bound),
  - Then starts ripping (re-encoding into mpeg) and becomes CPU-bound
  - Scheduling should match program phases

Dynamic priority

$$\textit{dynamic priority} = \max(100, \min((\textit{static priority} - \textit{bonus} + 5), 139))$$

- Bonus is calculated based on sleep time
- Dynamic priority determines a tasks' runqueue
- This is a heuristic to balance competing goals of CPU throughput and latency in dealing with infrequent I/O
  - May not be optimal

Dynamic priority in O(1)

- Important: The runqueue a process goes in is determined by the **dynamic** priority, not the static priority
  - Dynamic priority is mostly determined by time spent waiting, to boost UI responsiveness
- Nice values influence **static** priority
  - No matter how “nice” you are (or aren’t), you can’t boost your dynamic priority without blocking on a wait queue!

Completely Fair Scheduler
Linux 2.6.23 - now

Fairness

- Each task makes proportional progress on the CPU
  - No starvation

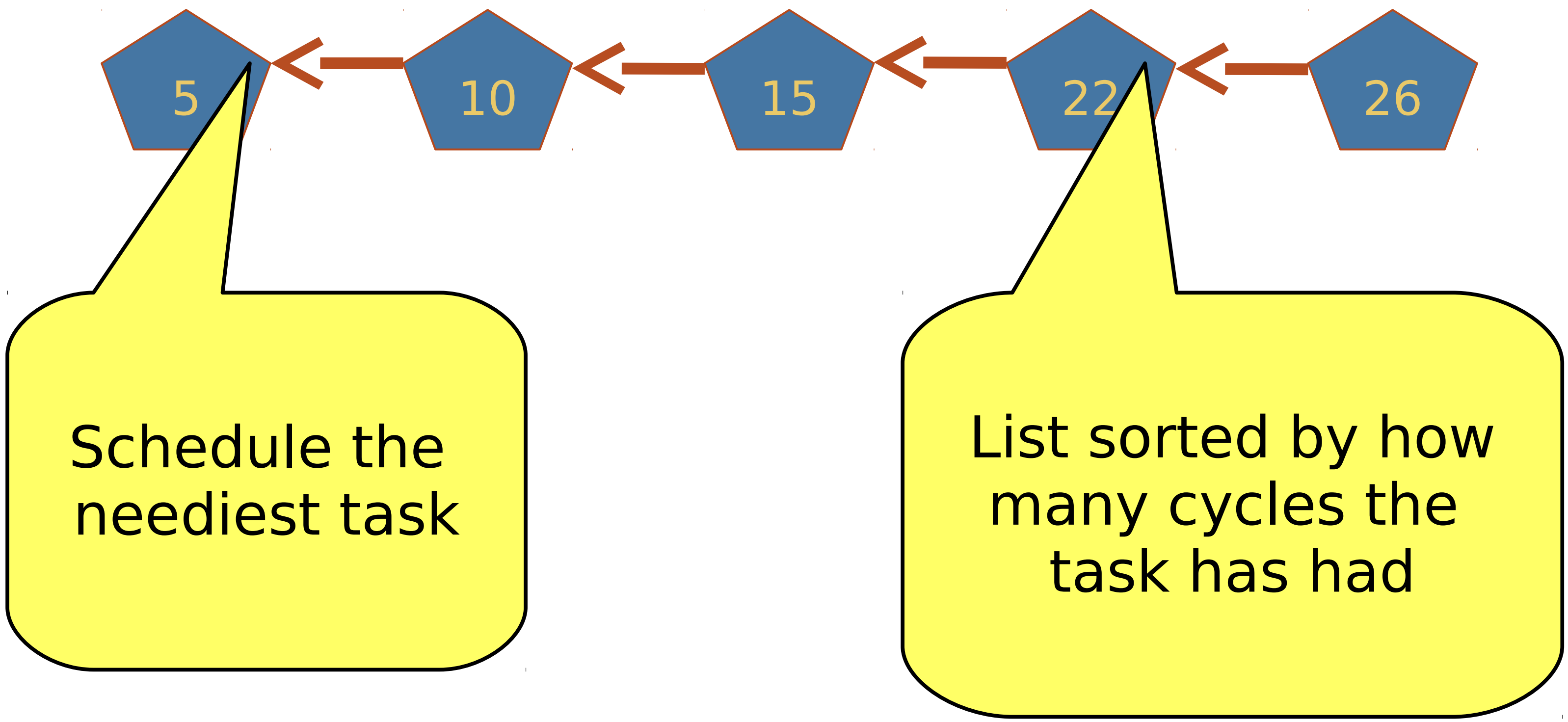
Problems with O(1)

- Heuristics became hard
  - Hard to maintain and make sense of

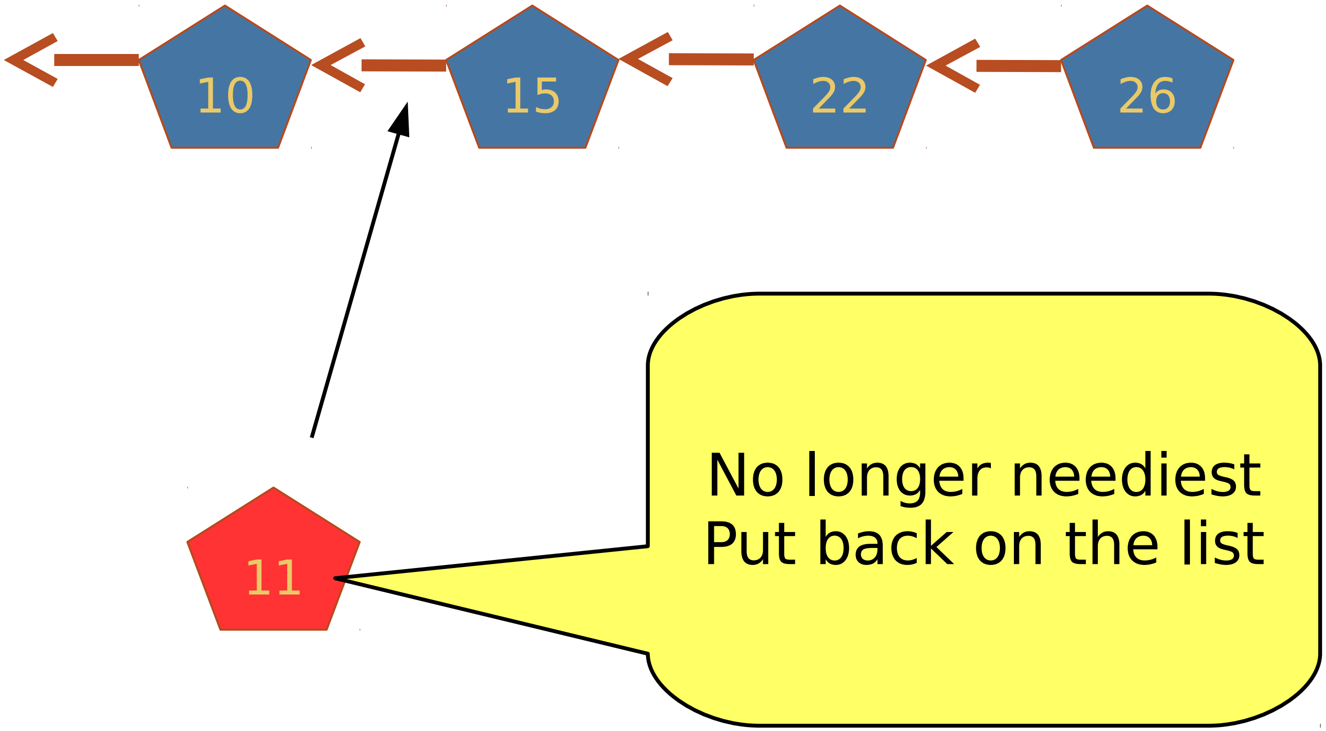
CFS idea

- Back to a simple list of tasks (conceptually)
  - Ordered by how much time they ran
  - Least time to most time
- Always pick the “neediest” task to run
  - Until it is no longer neediest
  - Then re-insert old task in the timeline
  - Schedule the new neediest

CFS example


5
10
15
22
26
Schedule the neediest task
List sorted by how many cycles the task has had

CFS example



Lists are inefficient

- That's why we really use a tree
  - Red-black tree: 9/10 Linux developers recommend it
- log(n) time for:
  - Picking next task (i.e., search for left-most task)
  - Putting the task back when it is done (i.e., insertion)
  - Remember: n is total number of tasks on system

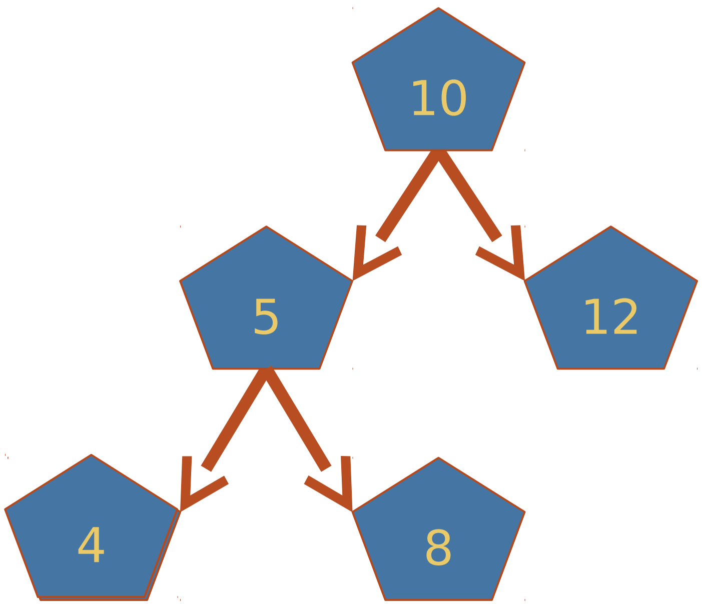
CPU time accounting

- Global virtual clock: ticks at a fraction of real time
  - Fraction is number of total tasks
- Each task counts how many clock ticks it has had
- Example: 4 tasks
  - Global vclock ticks once every 4 real ticks
  - Each task scheduled for one real tick; advances local clock by one tick

More details

- Task’s ticks make key in RB-tree
  - Fewest tick count get serviced first
- No more runqueues
  - Just a single tree-structured timeline

CFS example



- Tasks sorted by ticks executed
- Global ticks = 12
- One global tick per n ticks
  - n == number of tasks (5)
- 4 ticks for first task
  - Reinsert into the list
- 1 tick to new first task
  - Increment global clock

New tasks

- What about a new task?
  - If task ticks start at zero, doesn’t it get to unfairly run for a long time?
- Strategies:
  - Could initialize to current time (start at right)
  - Could get half of parent’s deficit

Priorities

- In CFS, priorities weigh the length of a task’s “tick”
- Example:
  - For a high-priority task, a virtual, task-local tick may last for 10 actual clock ticks
  - For a low-priority task, a virtual, task-local tick may only last for 1 actual clock tick
- Result: Higher-priority tasks run longer, low-priority tasks make some progress

Interactivity

- Recall: GUI programs are I/O bound
  - We want them to be responsive to user input
  - Need to be scheduled as soon as input is available
  - Will only run for a short time

GUI programs

- Just like O(1) scheduler, CFS takes blocked programs out of the RB-tree of runnable processes
- Virtual clock continues ticking while tasks are blocked
  - Increasingly large deficit between task and global vclock
- When a GUI task is runnable, generally goes to the front
  - Dramatically lower vclock value than CPU-bound jobs
  - Reminder: “front” is left side of tree

Other refinements

- User A has 1 job, user B has 99
  - B will get 99% of CPU time
  - We want A and B split CPU in half

- Per group or user scheduling
  - Real to virtual tick ratio becomes a function of number of both global and user's/group's tasks

Group scheduling

- Per group or user scheduling
  - Real to virtual tick ratio becomes a function of number of both global and user's/group's tasks

Real-time scheduling

Real-time scheduling

- Different model: need to do a modest amount of work by a deadline
- Example:
  - Audio application needs to deliver a frame every nth of a second
  - Too many or too few frames unpleasant to hear

Strawman

- If I know it takes n ticks to process a frame of audio, just schedule my application n ticks before the deadline
- Problems?
- Hard to accurately estimate n
  - Interrupts
  - Cache misses
  - Disk accesses
  - Variable execution time depending on inputs

Hard problem

- Gets even worse with multiple applications + deadlines
- May not be able to meet all deadlines
- Interactions through shared data structures worsen variability
  - Block on locks held by other tasks
  - Cached CPU, TLB, and file system data gets evicted

Real-time scheduling in Linux

- Linux has soft-real time scheduling
  - No hard real-time guarantees
- All real-time tasks are higher priority than any conventional process
  - Priorities 0 – 99
- Assumption: like GUI programs, RR tasks will spend most of their time blocked on I/O
  - Latency is key concern

Real-time policies

- First-in, first-out: SCHED_FIFO
  - Static priority
  - Process is only preempted for a higher priority process
  - No time quanta; it runs until its done, blocked or yields voluntarily
- Round robin: SCHED_RR
  - Same as above but with a time quanta (800ms)

Accounting kernel time

- Should time spent in the OS count against an application’s time slice?
  - Yes: Time in a system call is work on behalf of that task
  - No: Time in an interrupt handler may be completing I/O for another task

Latency of system calls

- System call times vary
- Context switches are generally at system call boundary
  - Can also context switch on blocking I/O operations
- If a time slice expires inside of a system call:
  - Task gets rest of system call “for free”
  - Steals from next task
  - Potentially delays interactive/real time task until finished

Idea: kernel preemption

- Why not preempt system calls just like user code?
- Well, because it is harder!
- Why?
  - May hold a lock that other tasks need to make progress
  - May be in a sequence of HW config options that assumes it won't be interrupted
- General strategy: allow fragile code to disable preemption
  - Interrupt handlers can disable interrupts if needed

Kernel preemption

- Implementation: actually not too bad
  - Essentially, it is transparently disabled with any locks held
  - A few other places disabled by hand
- Result: UI programs a bit more responsive

Conclusion

- O(1)
  - Two sets of runques
  - Each process has priority
- CFS
  - Queue of runnable tasks
  - Red/black tree for fast lookup and insertion
- Real-time
  - Run in front of O(1) or CFS scheduler
  - No good solution so far

Thank you!