CSE 506: Operating Systems

Scheduling

Undergrad Review

- 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 application more control
    - One task can hog the CPU forever
  - Preemptive gives OS more control
    - More overheads/complexity

Where can we preempt a process?

- When can the OS can regain control?
- System calls
  - Before
  - During
  - After
- Interrupts
  - Timer interrupt
    - Ensures maximum time slice
  - Keyboard, network, disk, …

(Linux) Terminology

- `mm_struct` – represents an address space in kernel
- `task` – represents a thread in the kernel
  - Traditionally called ***process control block (PCB)***
  - A task points to 0 or 1 `mm_structs`
    - Kernel threads just "borrow" previous task's mm
    - Possible because they only execute in high addresses
      - Shared by all processes
  - Multiple tasks can point to the same `mm_struct`
    - Multi-threading
- Quantum – CPU timeslice

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 don’t want slow GUI

No perfect solution

- Optimizing multiple variables
- Like memory allocation, this is best-effort
  - Some workloads prefer some scheduling strategies
- Some solutions are generally "better" than others

Context switching

- What is it?
  - Switch out the address space and running thread
- Address space:
  - Need to change page tables
    - Update CR3 register on x86
  - By convention, kernel at same address in all processes
    - What would be hard about mapping kernel in different places?

Other context switching tasks

- Switch out other register state
- Reclaim resources if needed
  - e.g,. if de-scheduling a process for the last time (on exit)
    - Exercise care – page tables/`mm_struct` still used by kernel
- Switch thread stacks
  - Assuming each thread has its own stack

Switching threads

- Programming abstraction:

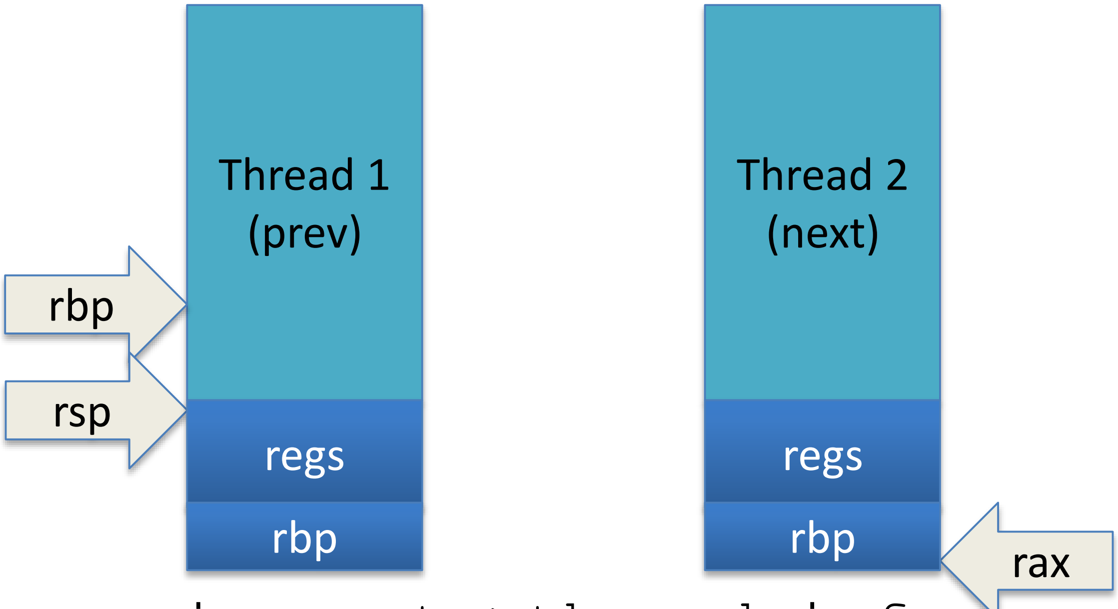
```
/* Do some work */
schedule(); /* Something else runs */
/* Do more work */
```

- Threads generally unaware of others
  - Calling `schedule()` can return immediately
  - Or it can return after a very long time (many threads run)

How to switch stacks?

- Store register state on stack in a well-defined format
- Carefully update stack register to new stack
  - Tricky: can't use stack-based storage for this step!
- Assumes each process has its own kernel stack
  - The "norm" in today's Oses
    - Just include kernel stack in the PCB
  - Not a strict requirement
    - Can use "one" stack for kernel (per CPU)
    - More headache and book-keeping

Example




```
/* rax is next->thread_info.rsp */
/* push general-purpose regs*/
push rbp
mov rax, rsp
pop rbp
/* pop general-purpose regs */
```

Weird code to write

- Inside schedule(), you end up with code like:

```
switch_to(me, next, &last);
/* possibly clean up last */
```

- Where does ***last*** come from?
  - Output of switch_to
  - Written on my stack by previous thread (not me)!

How to code this?

- rax: pointer to me
- rbx: pointer to last's location on my stack
- rcx: pointer to next

```
push rax /* ptr to me on my stack */
push rbx /* ptr to local last (&last) */
mov rsp,rax(10) /* save my stack ptr */
mov rcx(10),rsp /* switch to next stack */
pop rbx /* get next's ptr to &last */
mov rax,(rbx) /* store rax in &last */
pop rax /* Update me (rax) to new task */
```

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?
  - Only allows round-robin scheduling
  - Can’t prioritize tasks

Even straw-ier man

- Naïve approach to priorities:
  - Scan the entire list on each run
  - Or periodically reshuffle the list
- Problems:
  - Forking – where does child go?
  - What about if you only use part of your quantum?
    - E.g., blocking I/O

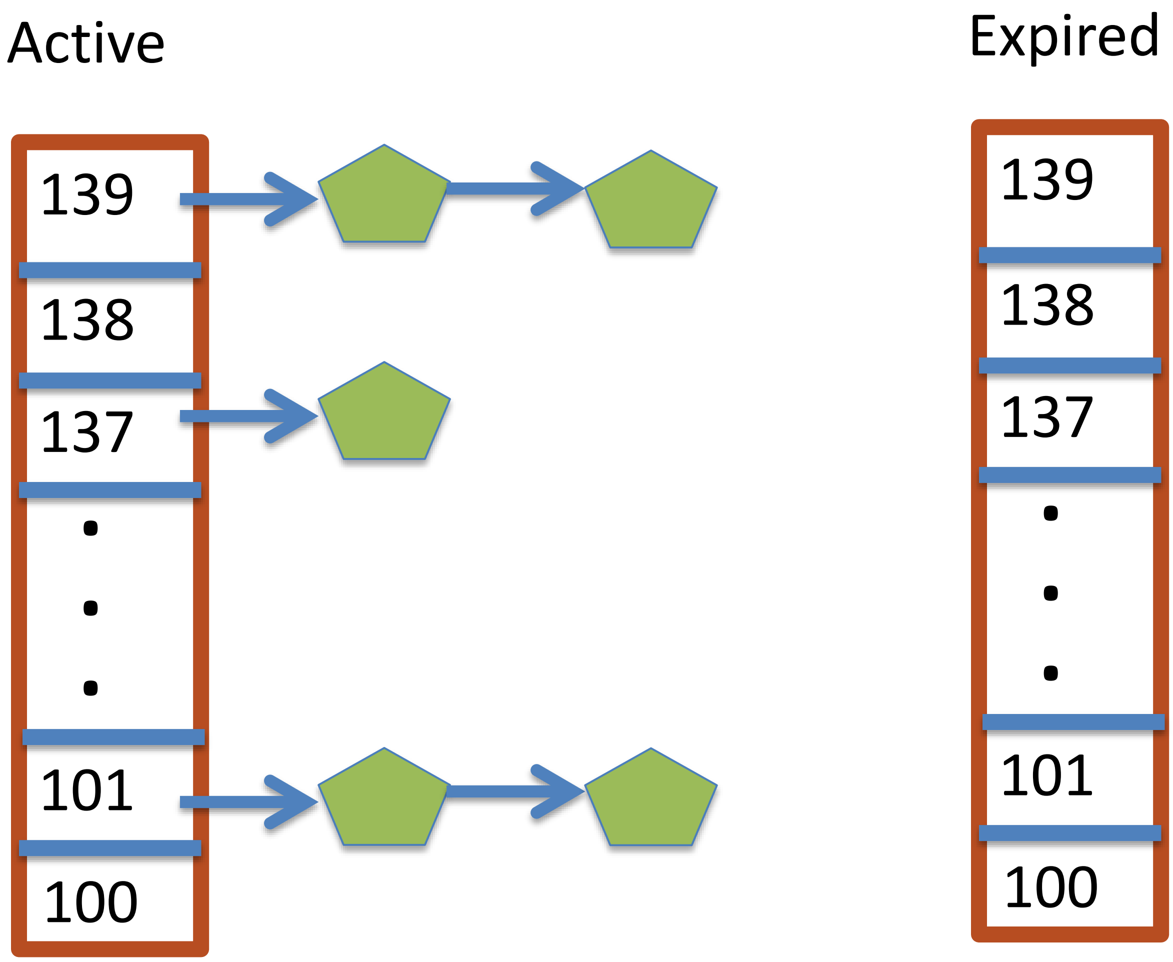
O(1) scheduler

- 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) Bookkeeping

- 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 on this later)
  - 2 sets of runqueues – one active and one expired

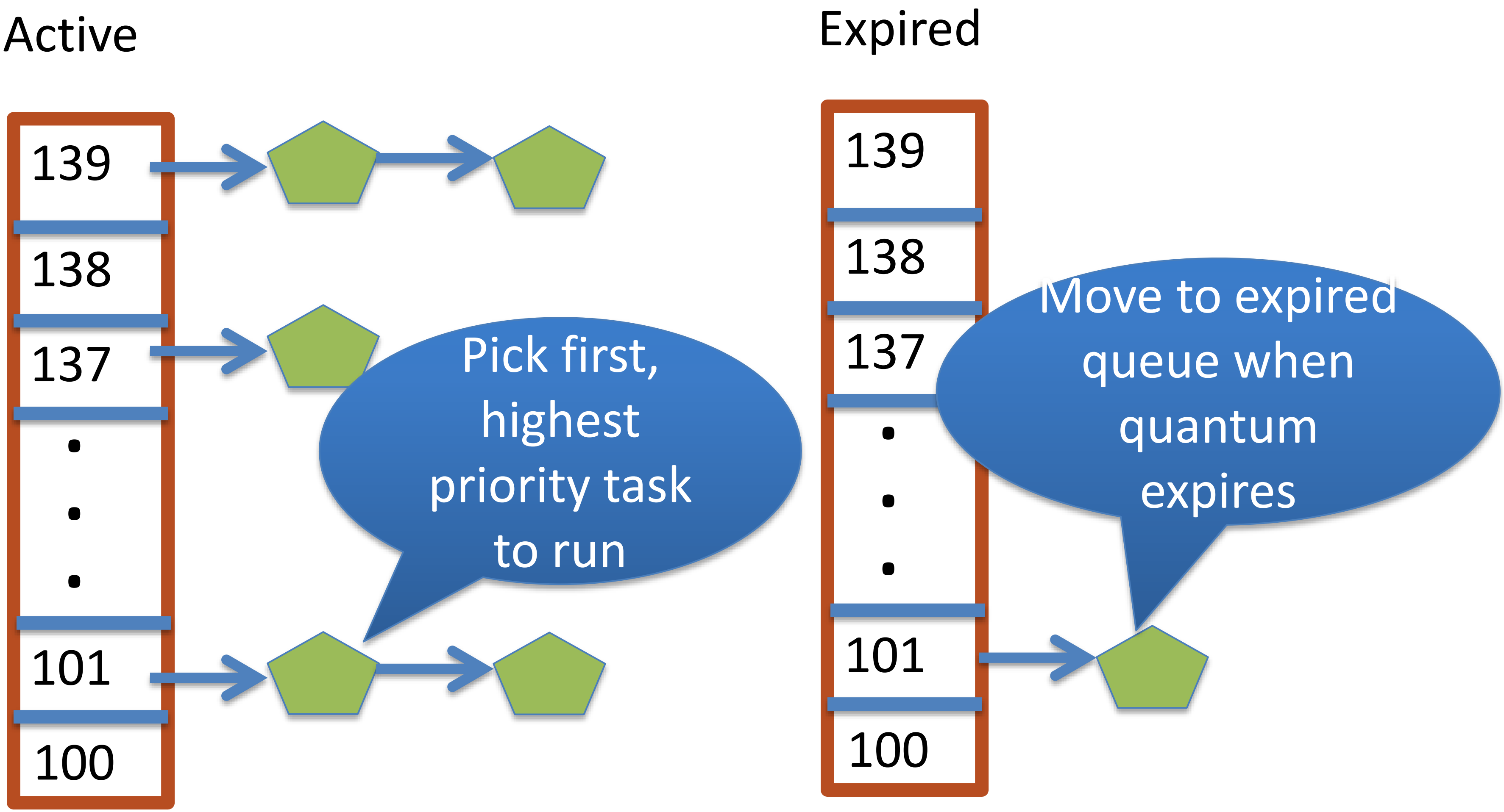
O(1) Data Structures



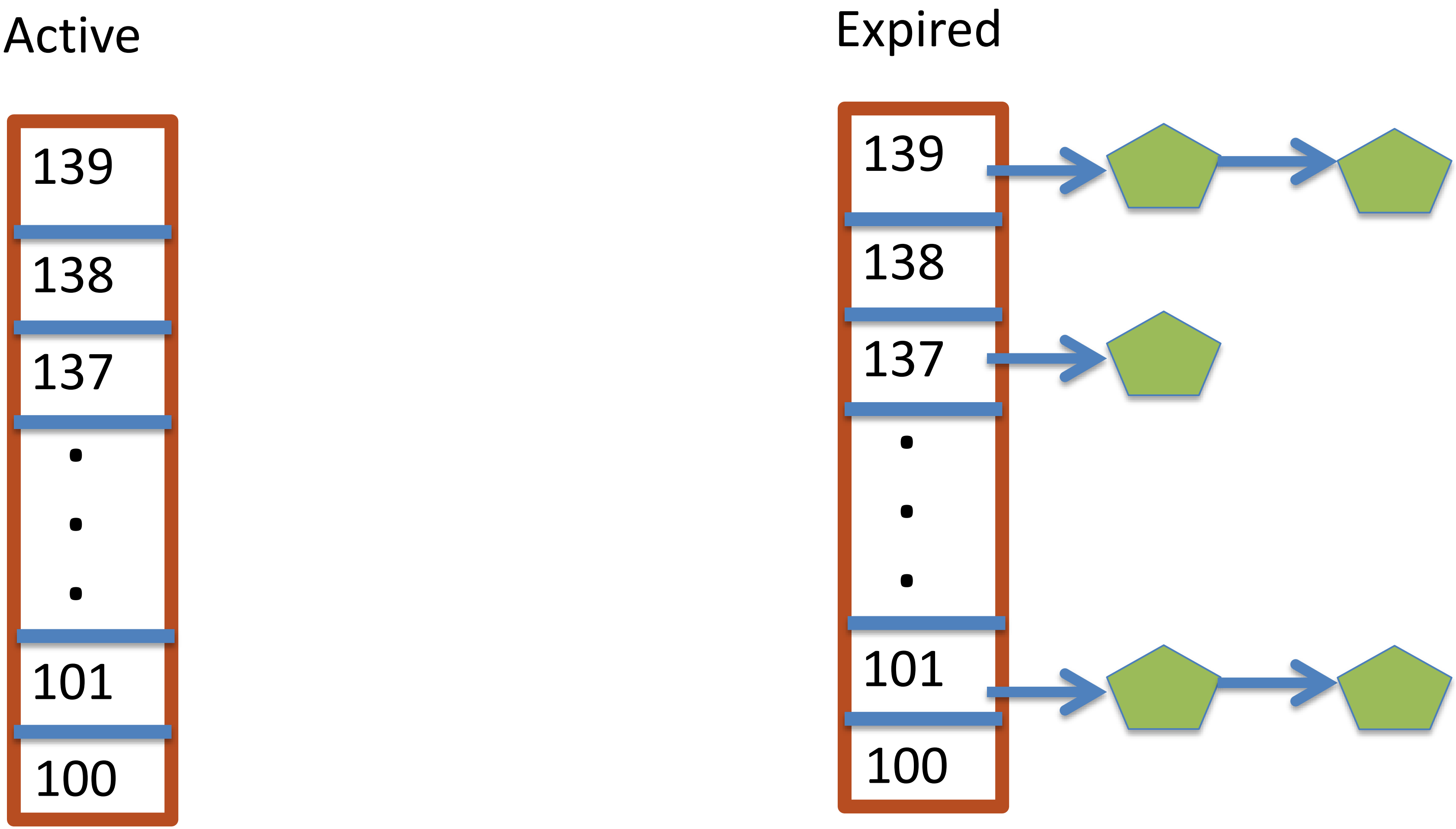
O(1) Intuition

- Take first task from lowest runqueue on active set
  - Confusingly: a lower priority value means higher priority
- When done, put it on runqueue on expired set
- On empty active, swap active and expired runqueues
- Constant time
  - 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 expired queue when quantum expires

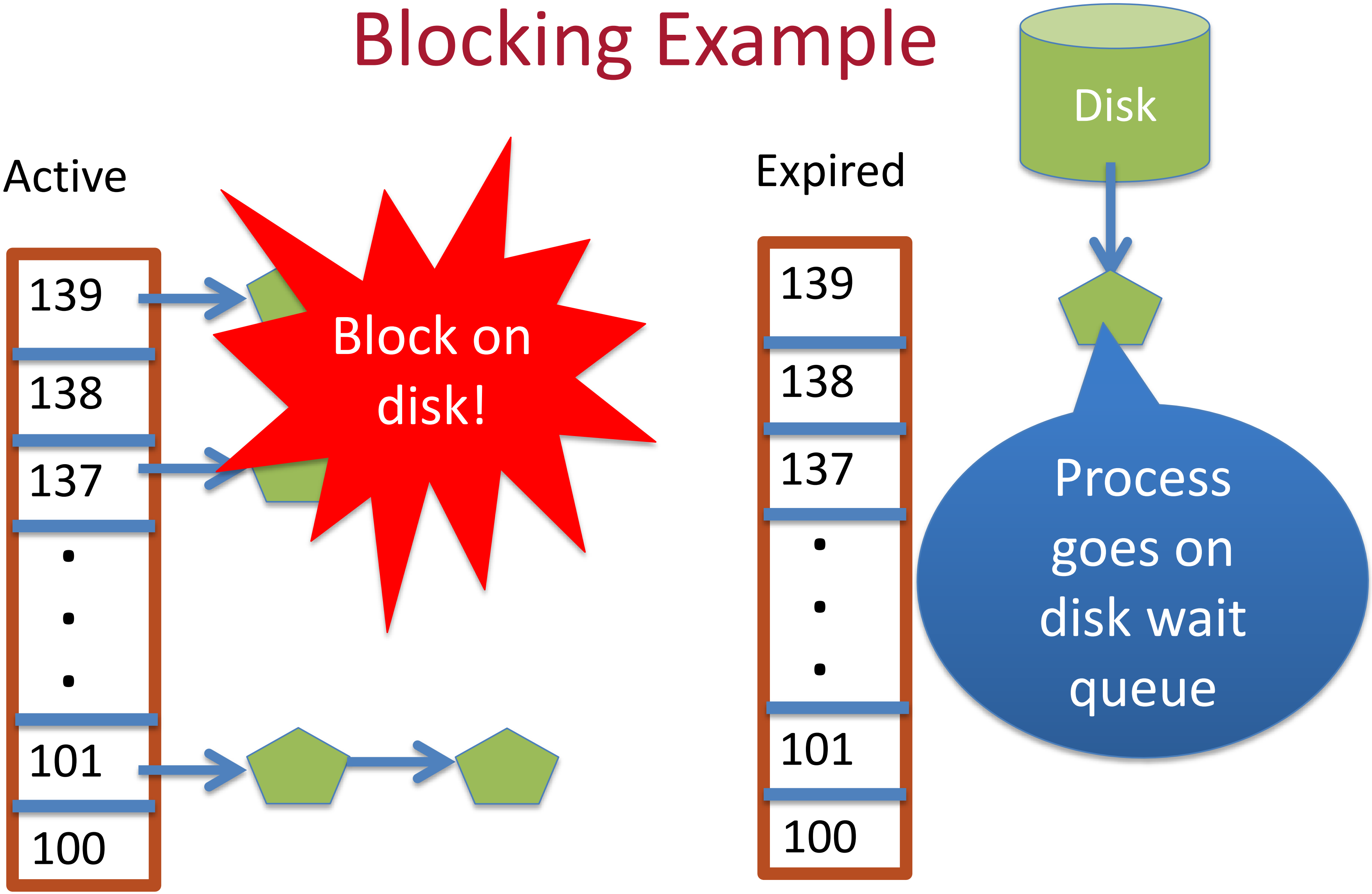
What now?



Blocked Tasks

- What if a program blocks on I/O, say for the disk?
  - It still has part of its quantum left
  - Not runnable
    - Don’t put on the active or expired runqueues
- Need a “wait queue” for each blocking event
  - Disk, lock, pipe, network socket, etc…

Blocking Example



Blocked Tasks, cont.

- A blocked task is moved to a wait queue
  - Moved back when expected event happens
  - No longer on any active or expired queue!
- Disk example:
  - I/O finishes, IRQ handler puts task on active runqueue

Time slice tracking

- A process blocks and then becomes runnable
  - How do we know how much time it had left?
- Each task tracks time left in ‘time_slice’ field
  - On each clock period: 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
- 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

$$time = \begin{cases} (140 - prio) * 20ms & prio < 120 \\ (140 - prio) * 5ms & prio \geq 120 \end{cases}$$

- "Higher" priority tasks get longer time slices
  - And run first

Goal: Responsive UIs

- Most GUI programs are I/O bound on the user
  - Unlikely to use entire time slice
- Users annoyed if keypress takes 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 wait on I/O
- Monitor I/O wait time
  - 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
    - Then it is CPU bound to encode to mp3
  - Scheduling should match program phases

Dynamic priority

- priority=max(100,min(static priority−bonus+5,139))
- Bonus is calculated based on sleep time
- Dynamic priority determines a tasks' runqueue
- Balance throughput and latency with infrequent I/O
  - May not be optimal
- Call it what you prefer
  - Carefully studied battle-tested heuristic
  - Horrible hack that seems to work

Dynamic Priority in O(1) Scheduler

- Runqueue determined by the dynamic priority
  - Not the static priority
  - Dynamic priority mostly based on time spent waiting
    - To boost UI responsiveness and "fairness" to I/O intensive apps
- "`nice`" values influence static priority
  - Can't boost dynamic priority without being in wait queue!
  - No matter how "nice" you are (or aren't)

Average load

- How do we measure how busy a CPU is?
- Average number of runnable tasks over time
- Available in /proc/loadavg

Setting priorities

- setpriority(which, who, niceval) and getpriority()
  - Which: process, process group, or user id
  - PID, PGID, or UID
  - Niceval: -20 to +19 (recall earlier)
- nice(niceval)
  - Historical interface (backwards compatible)
  - Equivalent to:
    - setpriority(PRIO_PROCESS, getpid(), niceval)

yield()

- Moves a runnable task to the expired runqueue
  - Unless real-time, move to the end of the active runqueue
- Several other real-time related APIs

How about a "better" scheduler?

- O(1) scheduler – older Linux scheduler
  - Today: Completely Fair Scheduler (CFS) – new hotness
- Other advanced scheduling issues
  - Real-time scheduling
  - Kernel preemption

Fair Scheduling

- Idea: 50 tasks, each should get 2% of CPU time
- Do we really want this?
  - What about priorities?
  - Interactive vs. batch jobs?
  - Per-user fairness?
    - Alice has 1 task and Bob has 49; why should Bob get 98% of CPU?

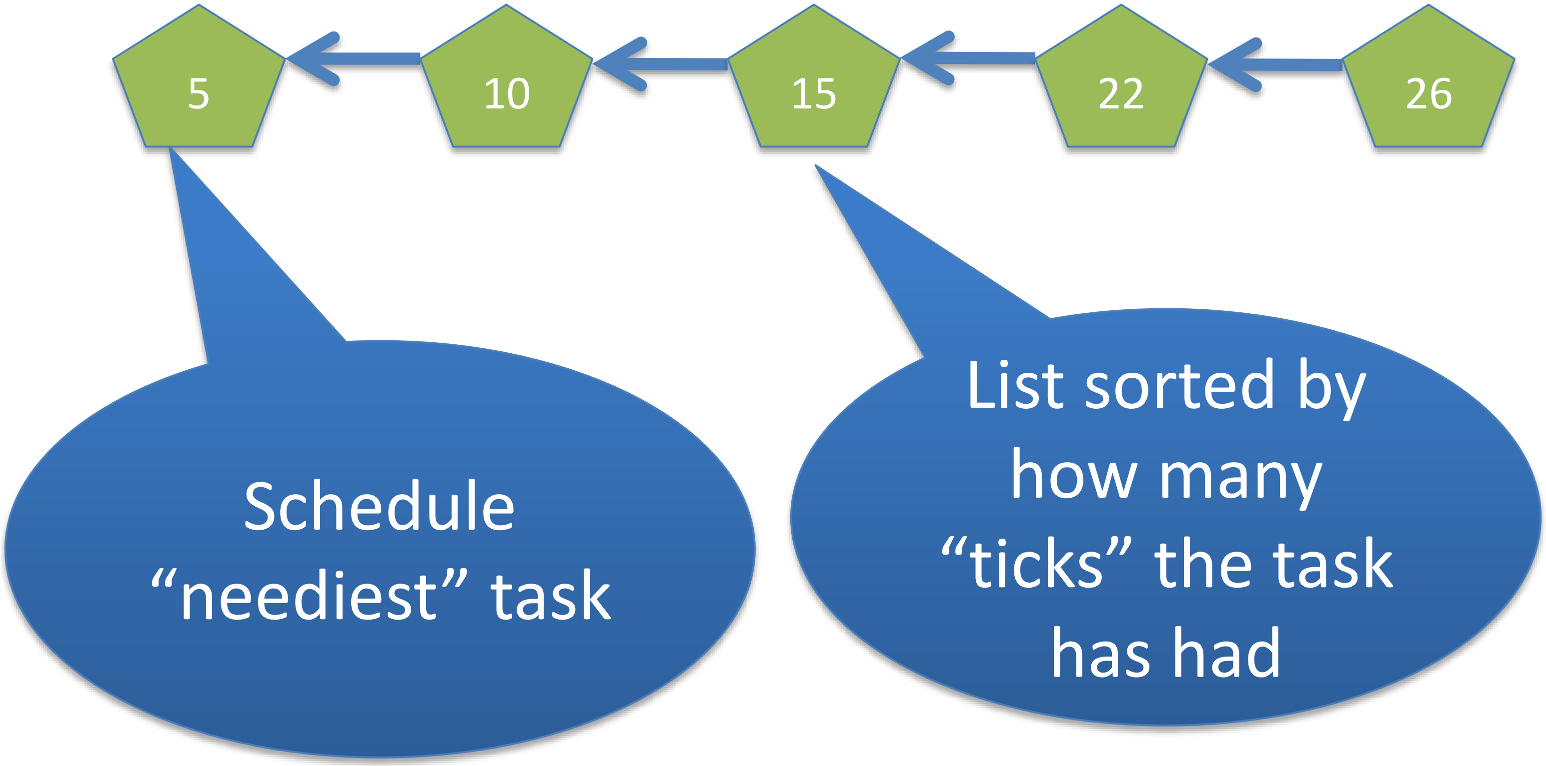
If you thought O(1) was a hack…

- Real issue: O(1) scheduler is complicated
  - Heuristics for various issues makes it more complicated
  - Heuristics can end up working at cross-purposes
- Software engineering observation
  - If kernel devs. understood scheduling and workloads
    - Could make more informed design choice
- If you prefer elegance
  - Structure (and complexity) of solution matches problem

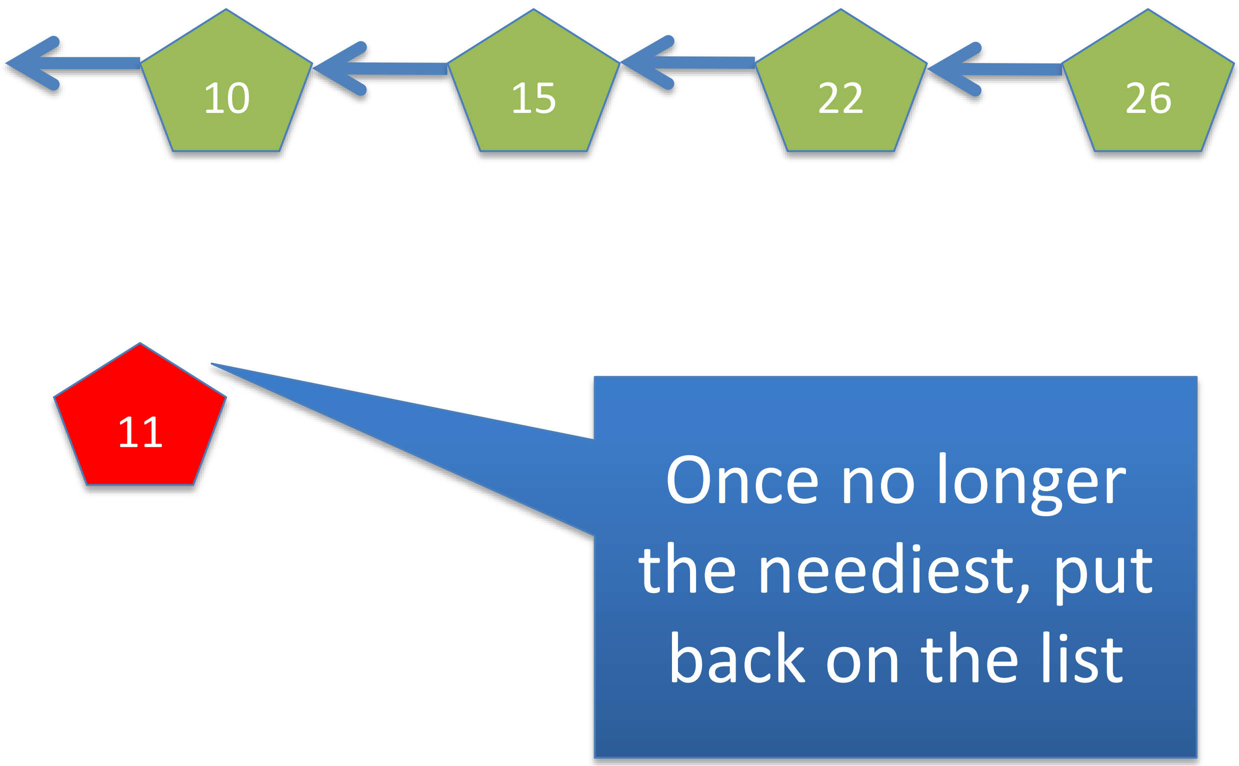
CFS idea

- Back to a simple list of tasks (conceptually)
- Ordered by how much time they've had
  - 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 "neediest" task
List sorted by how many "ticks" the task has had

CFS Example



But lists are inefficient

- Duh! 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

Details

- 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 real tick

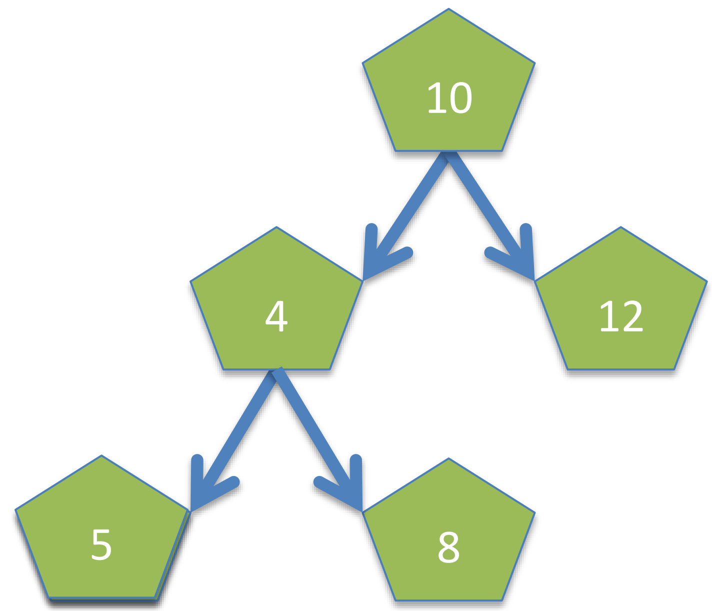
More details

- Task's ticks make key in RB-tree
  - Lowest tick count gets serviced first
- No more runqueues
  - Just a single tree-structured timeline

CFS Example (more realistic)

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

Global Ticks: 12



Edge case 1

- What about a new task?
  - If task ticks start at zero, unfairly run for a long time?
- Strategies:
  - Could initialize to current time (start at right)
  - Could get half of parent's deficit

What happened to priorities?

- Priorities let me be del
  - This is a useful feature
- In CFS, priorities weigh k”
- 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
- Higher-priority tasks run longer
- Low-priority tasks make some progress

Note: 10:1 ratio is a made-up example. See code for real weights. (heuristics/hacks)

Interactive latency

- 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 program strategy

- CFS blocked tasks removed from RB-tree
  - Just like O(1) scheduler
- Virtual clock keeps ticking while tasks are blocked
  - Increasingly large deficit between task and global vclock
- When a GUI task is runnable, goes to the front
  - Dramatically lower vclock value than CPU-bound jobs

Other refinements

- Per group or user scheduling
  - Controlled by real to virtual tick ratio
    - Function of number of global and user's/group's tasks

Recap: Ticks galore!

- Real time is measured by a timer device
  - "ticks" at a certain frequency by raising a timer interrupt
- A process's virtual tick is some number of real ticks
  - Priorities, per-user fairness, etc... done by tuning this ratio
- Global ticks tracks max virtual ticks any process had
  - Used to calculate one's deficit

CFS Summary

- Idea: logically a queue of runnable tasks
  - Ordered by who has had the least CPU time
- Implemented with a tree for fast lookup
- Global clock counts virtual ticks
  - One tick per task count real ticks
- Features/tweaks (e.g., prio) are hacks
  - Implemented by playing games with length of a virtual tick
  - Virtual ticks vary in wall-clock length per-process

Real-time scheduling

- Different model
  - Must do modest amount of work by a deadline
- Example:
  - Audio application must deliver a frame every n ms
  - Too many or too few frames unpleasant to hear

Strawman

- If I know it takes n ticks to process a frame of audio
  – 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 harder w/multiple applications + deadlines
- May not be able to meet all deadlines
- Shared data structures worsen variability
  - Block on locks held by other tasks
  - Cached file system data gets evicted

Simple hack

- Real-time tasks get highest-priority scheduling class
  - SCHED_RR – RR == round robin
- RR tasks fairly divide CPU time amongst themselves
  - Pray that it is enough to meet deadlines
  - If so, other tasks share the left-overs
    - Other tasks may never get to run
- Assumption: RR tasks mostly blocked on I/O
  - Like GUI programs
  - Latency is the key concern

Next issue: Kernel time

- Should time spent in OS count against task?
  - Yes: Time in system call is work on behalf of that task
  - No: Time in IRQ handler may complete I/O for other task

Timeslices + syscalls

- System call times vary
- Context switches 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, duh!
- Why?
  - May hold a lock that other tasks need to make progress
  - May be in a sequence of HW config options
    - Usually assumes sequence won't be interrupted
- General strategy: fragile code disables preemption
  - Like IRQ handlers disabling 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
  - Harder to do without per-thread stacks
- Result: UI programs a bit more responsive