Virtualizing the CPU: Scheduling, Context Switching & Multithreading

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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

(Linux) Terminology

- `mm_struct` – represents an address space in kernel
- `task_struct` – represents a thread in the kernel
  - Traditionally called ***process control block (PCB)***
  - A `task_struct` points to a `mm_struct` to represent its address space
  - Many tasks can point to the same `mm_struct`
    - Multi-threading (topic of the next lecture)
- Quantum – CPU timeslice

Context Switching

Context Switching

- What is it?
  - Switch out the running thread context and possibly the address space
- 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?
- Thread context:
  - Save and restore general purpose registers
  - Switch the stack

Other Context Switching Tasks

- Switch out other thread state
  - Other register state if used
    - Segment selectors (fs and gs)
    - Floating point registers
    - Debugging registers
    - Performance counters
  - Update TSS
- Reclaim resources if needed
  - E.g,. if de-scheduling a process for the last time (on exit) reclaim its memory

Switching Threads

- Programming abstraction:

```
/* Do some work */

schedule();  // Choose Something else
             // to run & switch to it

/* Do more work */
```

`schedule()` in a Nutshell

```
schedule() {
        struct task_struct *prev, *next, *last;
        …
        prev = current;        // current thread
        next = …               // next thread to switch to
        …
        …
        switch_to(prev, next, last);

        // clean up last if need be
        // etc.
}
```

Running in `prev`'s context

Running in `next`'s context

- In `switch_to()`, `prev`'s registers are saved, stacks are switched and `next`'s registers are restored
- Where does `last` come from?
  - Output of `switch_to`
  - Written on my stack by previous thread (not me)!

What Happens in `switch_to()`?

DANGER! Do not use the stack while doing this.

- Lots of inline assembly code
  - Totally architecture specific — we assume x86.
- Push `prev`'s registers on the current stack
- Save `prev`'s stack pointer to its `task_struct`
- Restore `next`'s stack pointer from its `task_struct`
- Pop `next`'s registers from the new stack
- We assume each process has its own kernel stack
  - Common in modern OSes
  - **Note:** We're discussing context switch while in the kernel so the current stack is the kernel stack

How to Code This?

- `rax`: pointer to `prev`; `rcx`: pointer to `next`
- `rbx`: pointer to `last`'s location on my stack
- `OFFS`: offset of stack pointer value in task_struct
- Make sure `rbx` is pushed after `rax`

Push Regs
```
push rax                /* ptr to me on my stack */
push rbx                /* ptr to local last (&last) */
```

Switch Stacks
```
mov rsp, OFFS(rax)  /* save my stack ptr */
mov OFFS(rcx), rsp  /* switch to next stack */
```

Pop Regs
```
pop rbx                 /* get next's ptr to &last */
mov rax,(rbx)           /* store rax in &last */
pop rax                 /* Update me to new task */
```

Scheduling Policy & Algorithms

Policy Goals

- Fairness – everyone gets a fair share of the CPU
- User priorities
  - Virus scanning is nice, but don't want slow GUI
- Latency vs. Throughput
  - GUI programs should feel responsive (latency sensitive)
  - CPU-bound jobs want long CPU time (throughput sensitive)
  - Application's behavior can change over time

    → Policy needs to dynamically adapt to changes in application behavior
- Real-time deadlines
  - CPU time before a deadline more valuable than time after

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

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
- Problems?
  - Only allows round-robin scheduling
  - Can’t prioritize tasks
  - What if you only use part of your quantum (e.g., blocking I/O)?
  - How to support both latency-sensitive and throughput-sensitive applications?

(Old) Linux O(1) Scheduler

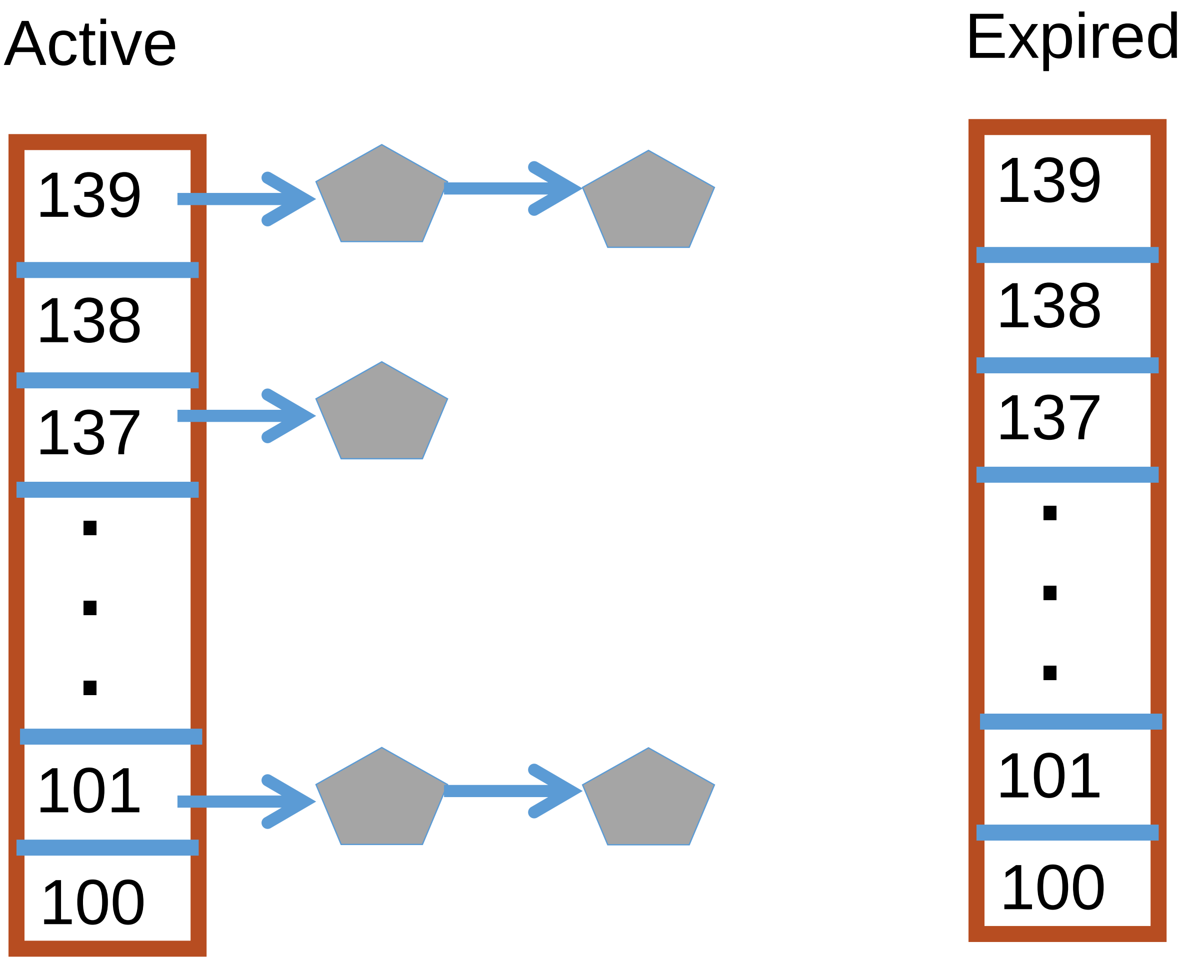
- Goal: decide who to run next
  - Independent of number of processes in system
  - Still maintain ability to
    - Prioritize tasks
    - Handle partially unused quanta
    - etc…

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 later)
  - 2 sets of runqueues – one <u>active</u> and one <u>expired</u>

Stony Brook University

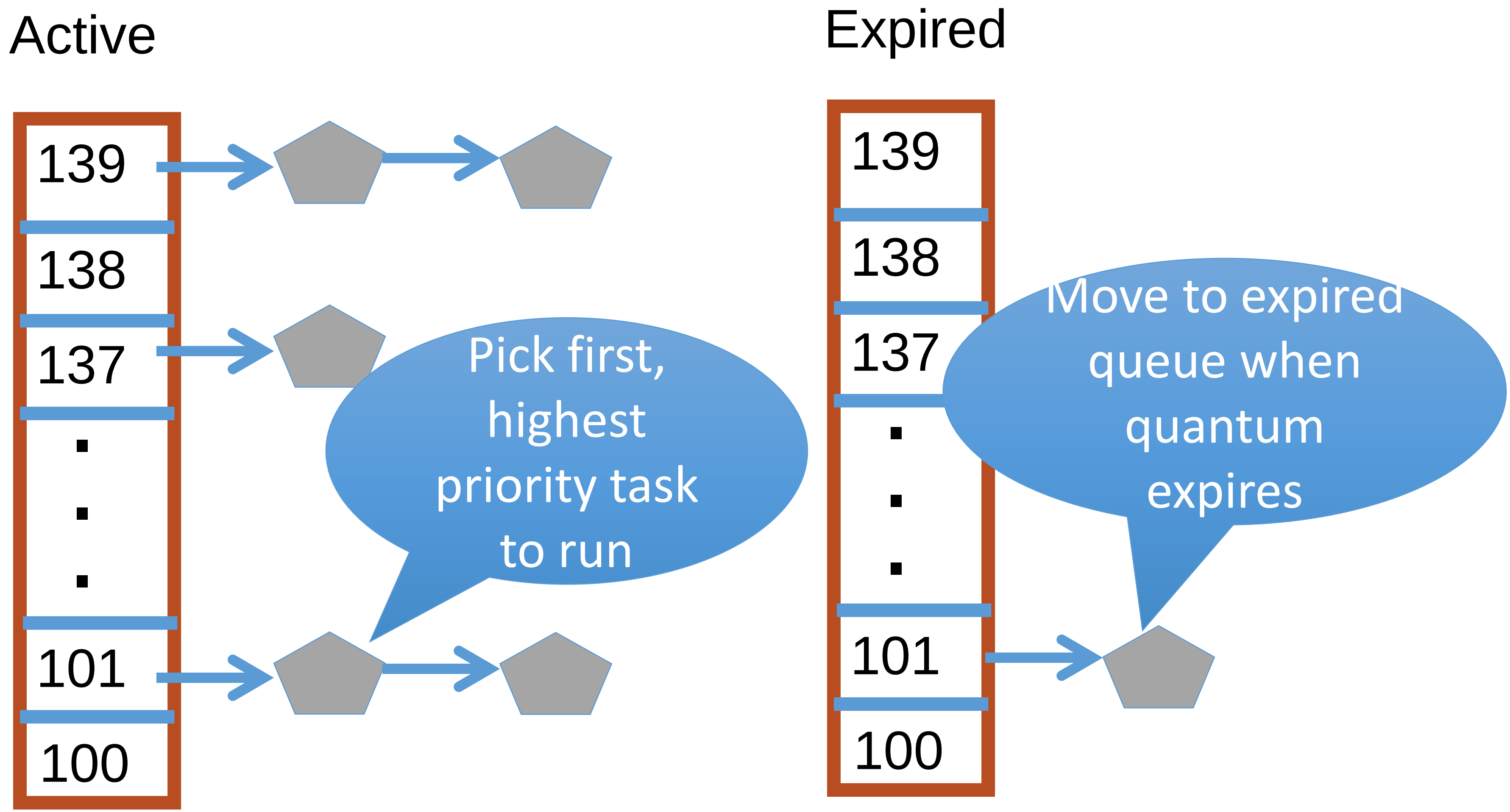
O(1) Data Structures



O(1) Intuition

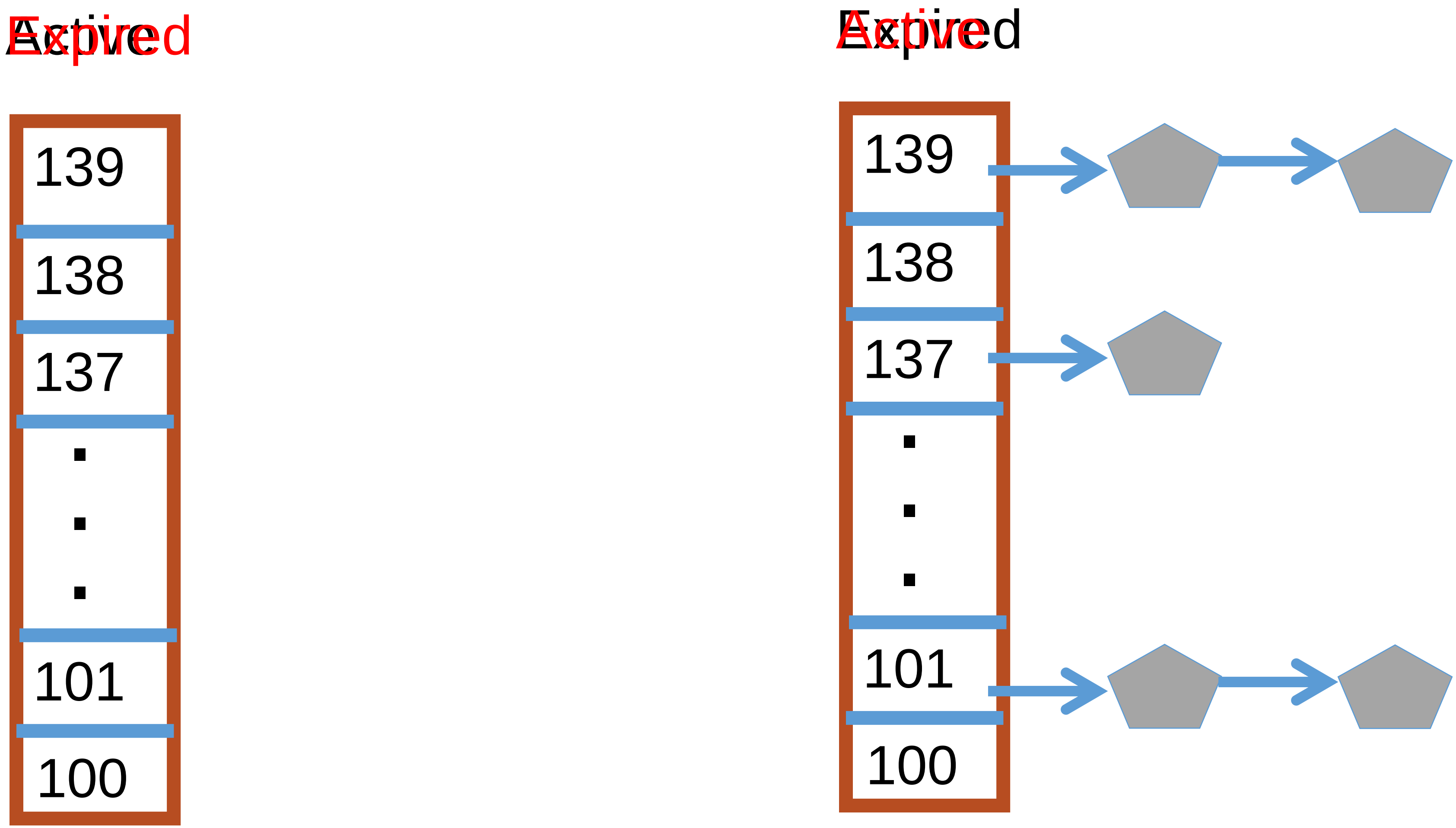
- Take first task from highest-priority runqueue on active set
- When done, put it on runqueue on expired set
- On empty active, swap active and expired runqueues
- Constant time
  - Fixed number of queues to check
  - Only take first item from non-empty queue

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

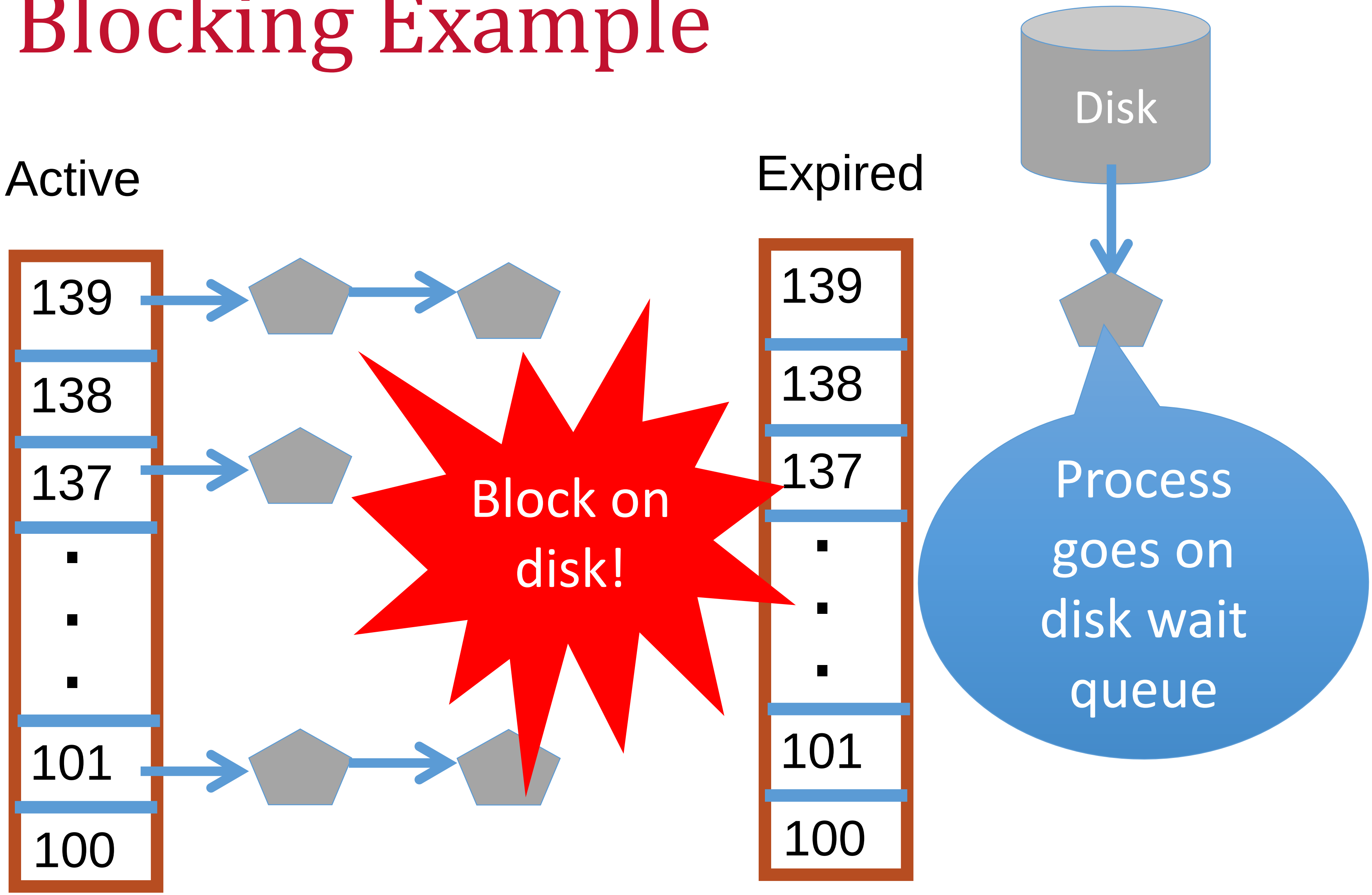
What Now?


Active
Expired
139
138
137
101
100
Expired
Active
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
    - 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 to active queue 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 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
- 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

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

- “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
- **Problem:** How to know 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 UI (and disk intensive)
- Give these applications a priority boost
- Note that this behavior can be dynamic
  - Example: DVD Ripper
    - UI configures DVD ripping
    - Then it is CPU bound to encode to mp3

  → Scheduling should match program phases

Dynamic Priority

- Dynamic priority
  $$= max(100, min(static\ priority - \mathbf{bonus} + 5, 139))$$
- ***Bonus*** is calculated based on sleep time
- Dynamic priority determines a task's 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

New Linux Scheduler: Completely Fair Scheduler (CFS)

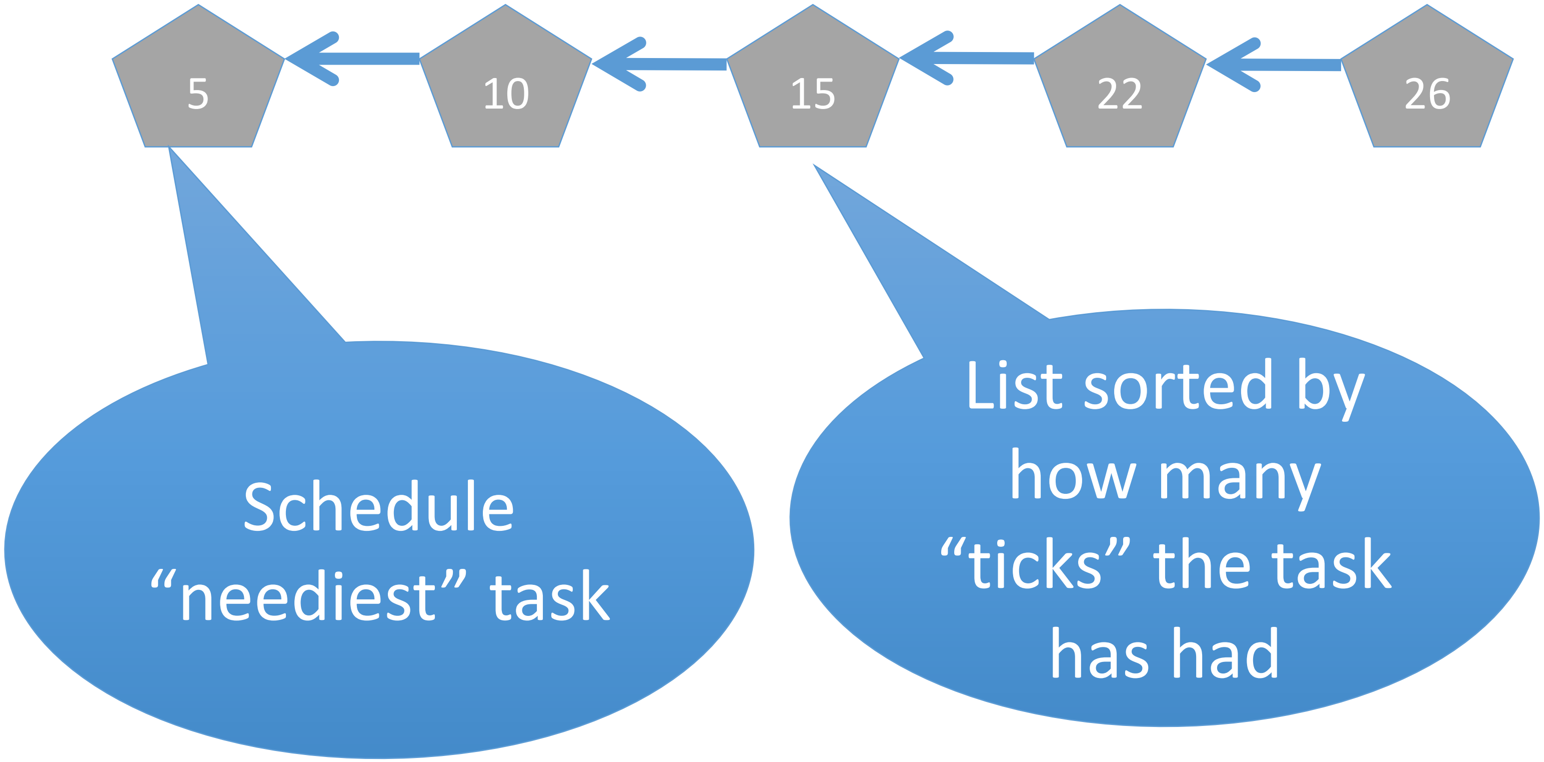
Fair Scheduling

- 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?
- ***Completely Fair Scheduler (CFS)***
  - Default Linux scheduler since 2.6.23

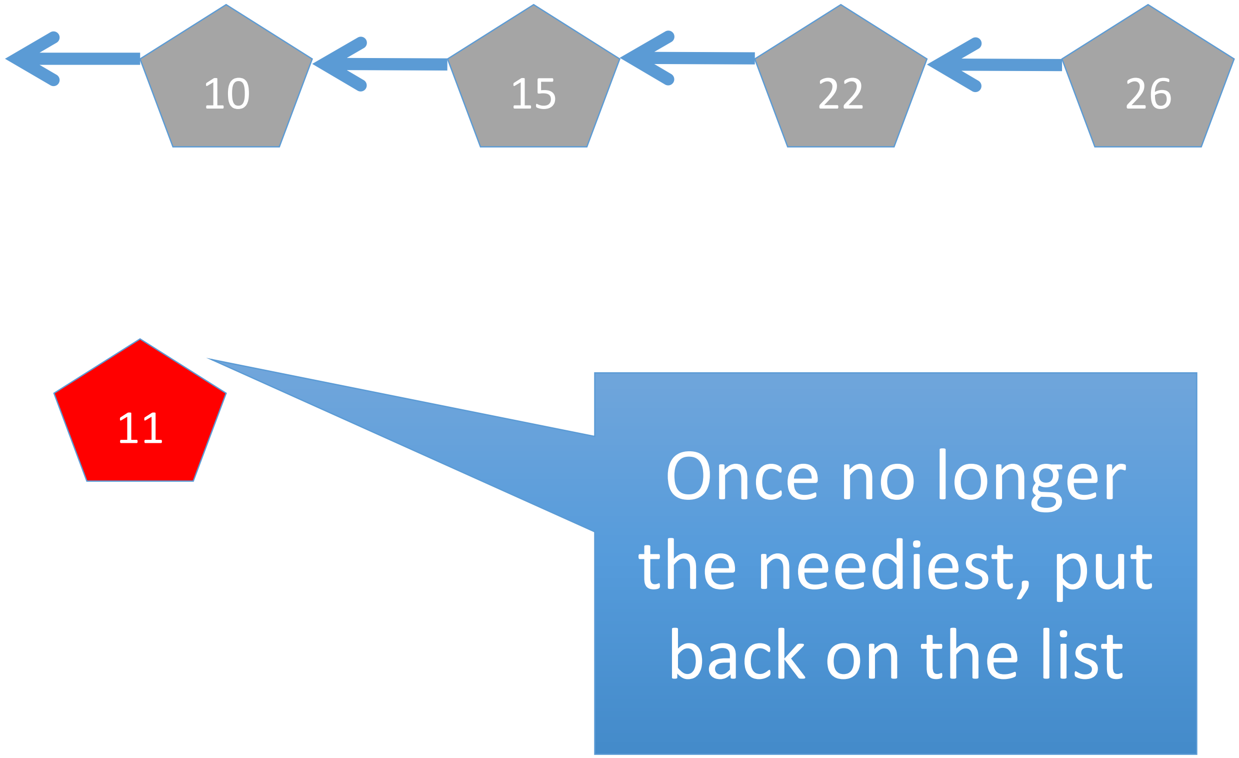
CFS idea

- Back to a simple list of tasks (conceptually)
- Ordered by how much time they have 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

- 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 = number of total tasks

  → Indicates "Fair" share of each task
- 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

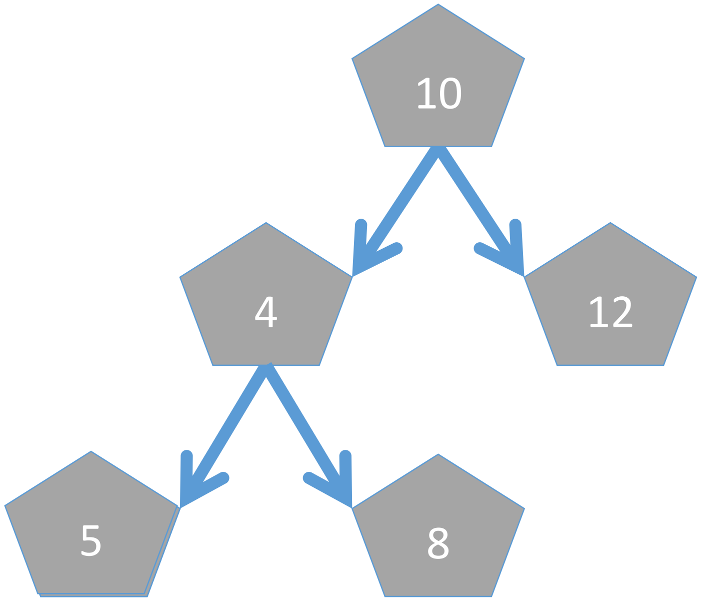
More Details

- 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: 8



Edge Case 1

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

What Happened to Priorities?

- Priorities let me be deliberately unfair
  - This is a useful feature
- In CFS, priorities weigh the len
- Example:
  - For a high-priority task
    - A task-local tick may last for 10 a clock ticks
  - For a low-priority task
    - A task-local tick may only last for 1 actual clock tick
- Higher-priority tasks run longer
- Low-priority tasks make some progress

10:1 ratio is a made-up example. See code for real weights.

Interactive Latency

- Recall: UI 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

UI Program Strategy

- Blocked tasks removed from RB-tree
  - Just like O(1) scheduler
- Global vclock 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 local-clock value than CPU-bound jobs

Other Refinements

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

Recap: Different Types of Ticks

- 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 the fair share of each process
  - Used to calculate one's deficit

CFS Summary

- Idea: logically a single 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

Other Issues

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

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

Linux's Hack

- Have different scheduling classes:
  - ***SCHED_IDLE***, ***SCHED_BATCH***, ***SCHED_OTHER***, ***SCHED_RR***, ***SCHED_FIFO***
- "Normal" tasks are in class *SCHED_OTHER*
- "Real-time" tasks get highest-priority scheduling class
  - *SCHED_RR* and *SCHED_FIFO* (RR: round robin)
  - RR is preemptive, FIFO is cooperative
- RR tasks fairly divide CPU time amongst themselves
  - Pray that it is enough to meet deadlines
  - Other tasks share the left-overs (if any)
- Assumption: RR tasks mostly blocked on I/O (likeGUI programs)
  - Latency is the key concern
- New scheduling class in recent Linux: ***SCHED_DEADLINE***
  - Highest priority class in system; Uses "Earliest Deadline First" scheduling
  - Details in http://man7.org/linux/man-pages/man7/sched.7.html

Linux Scheduling-Related API

- Includes many functions to set scheduling classes, priorities, processor affinities, yielding, etc.
- See http://man7.org/linux/man-pages/man7/sched.7.html for a detailed discussion

Next Issue: Average Load

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

Next Issue: Kernel Time

- Context switches generally at user/kernel boundary
  - Or on blocking I/O operations
- System call times vary
- Problems: if a time slice expires inside of a system call:
  1) Task gets rest of system call "for free"
     - Steals from next task
  2) 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: allow fragile code to disable 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
- Result: UI programs a bit more responsive

Threading

Threading Review

- Multiple threads of execution in one address space
  - Why?
    - Exploits multiple processors
    - Separate execution stream from address spaces, I/O descriptors, etc.
    - Improve responsiveness of UI (and similar applications)
- x86 hardware:
  - One CR3 register and set of page tables
    - Shared by 2+ different contexts (each has RIP, RSP, etc.)
- Linux:
  - One `mm_struct` shared by several `task_structs`

Threading Libraries

- Kernel provides basic functionality
  - e.g.: create new thread
- Threading library (e.g., libpthread) provides nice API
  - Thread management (join, cleanup, etc.)
  - Synchronization (mutex, condition variables, etc.)
  - Thread-local storage
- Part of design is division of labor
  - Between kernel and library

User vs. Kernel Threading

- Kernel threading
  - Every application-level thread is kernel-visible
    - Has its own `task_struct`
  - Called ***1:1 threading***
- User threading
  - Multiple application-level threads (*m*)
    - multiplexed on *n* kernel-visible threads (*m* >= *n*)
  - Context switching can be done in user space
    - Just a matter of saving/restoring all registers (including RSP!)
  - Called ***m:n threading***
    - Special case: ***m:1*** (no kernel support) — Cannot schedule multiple threads (of same process) across CPUs

User Threading Implementation

- User scheduler creates:
  - Analog of `task_struct` for each thread
    - Stores register state when switching
  - Stack for each thread
  - Some sort of run queue and scheduling policy
    - Can use any algorithm: simple round-robin, O(1), CFS, etc.
- Context switching similar to what we have seen already
  - Save/restore general purpose registers
  - Switch stacks

Tradeoffs of Threading Approaches

- Context switching overheads
- Finer-grained scheduling control
- Blocking I/O

Context Switching Overheads

- Takes a few hundred cycles to get in/out of kernel
  - Plus cost of saving/restoring registers
  - Plus cost of extra TLB/cache misses
- Time in the scheduler counts against your timeslice
- Forking a thread halves your time slice
  - At least in some schedulers
- 2 threads, 1 CPU
  - Run the context switch code in user-mode
    - Avoiding trap overheads, etc.
    - Get more time from the kernel

Finer-Grained Scheduling Control

- Example: Thread 1 has lock, Thread 2 waiting for lock
  - Thread 1's quantum expired
  - Thread 2 spinning until its quantum expires
  - Can donate Thread 2's quantum to Thread 1?
    - Both threads will make faster progress!
- Many examples (producer/consumer, barriers, etc.)
- Underlying problem:
  - Application's data and synchronization unknown to kernel

  → Kernel makes blind decisions

Blocking I/O

- I/O requires going to the kernel (generally)
- When one user thread does I/O
  - All other user threads in same kernel thread wait
- Solvable with async I/O (`aio` in Unix) and `poll()`-based programming
  - `aio` to avoid blocking on storage access
  - `poll()` to avoid blocking on network access
- Much more complicated to program
  - Still not a perfect solution

Recap: User Threading Complexity

- Lots of libc/libpthread changes
  - Especially, if designed to be application-transparent
  - Working around “unfriendly” blocking kernel API
- Bookkeeping gets much more complicated
  - Second scheduler
  - Synchronization different
- Preemption becomes complicated
  - Should use (expensive) timer signals from OS

→ Good user-mode threading needs better kernel/user interface

Proposal: Scheduler Activations

- **Required reading assignment**
- Better API for user-level threading
  - Not available on Linux
- On any blocking operation, kernel *upcalls* back to user scheduler
  - Eliminates most libc changes
  - Easier notification of blocking events
- User scheduler keeps kernel notified of how many runnable tasks it has (via system call)

Threading in Practice

- User-threading has come in and out of vogue
  - Correlated with efficiency of OS thread create and switch
- Linux 2.4 – Kernel threading was slow
  - User-level thread packages were hot (e.g., LinuxThreads)
    - Code is really complicated
      - Hard to maintain
      - Hard to tune
- Linux 2.6 – Substantial effort into tuning kernel threads
  - ***Native POSIX Threads Library*** (***NPTL***) — GNU implementation of the POSIX threads (`pthreads`) API
  - Most JVMs abandoned user threads
    - Tolerable performance at low complexity

Kernel Threading and Synch. Performance

- Consider implementing `pthread_mutex_lock/unlock`
  - Simple lock/unlock functionality
- When lock is uncontended, you want operations to be completely in user-mode
  - Avoid going to kernel (fast path)
- What if the lock is contended?
  - Thread 2 has to wait until Thread 1 releases the lock

Dealing with Contention

Two options:

1) Pure user-mode implementation: Thread 2 spins (busy-wait) until lock is released by Thread 1
   - Thread 2 spins until timeslice finishes → Thread 1 is scheduled back in, releases the lock, and finishes timeslice→ Thread 2 is scheduled and grabs the lock
   - Thread 2 wastes processor cycles
   - Gets worse as thread count grows

2) Use kernel's help: Thread 2 spins for a short while and then puts itself to sleep
   - Thread 1 has to wake it up after releasing the lock
   - How?

Dealing with Contention (2)

- How to wake up a sleeping thread waiting on a lock?
  - Old solution: send it a signal (more on signals in IPC lecture)
    - Complicated to implement and very slow
  - New solution: ***futex***

- Futex: essentially a shared wait queue in the kernel
- Idea:
  - (Fast path) use atomic instructions in user space to implement uncontended case for a lock (avoid going to kernel)
  - (Slow path) if task needs to block, ask the kernel to put you on a given futex wait queue
  - Task that releases the lock wakes up next task on the futex wait queue

- Futex improves NPTL synch. performance significantly, and simplify code compared to using signals
- **See optional reading on futexes for more details**