Scheduling, part 2

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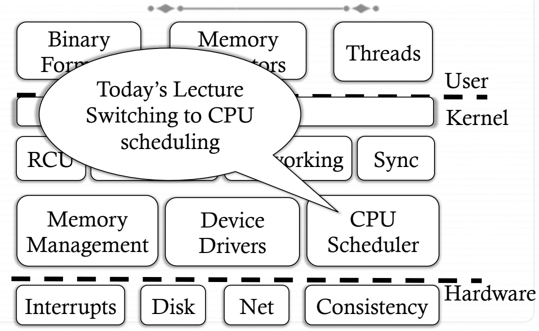
CSE 506

Logical Diagram



Last time…

- Scheduling overview, key trade-offs, etc.
- O(1) scheduler – older Linux scheduler
  - Today: Completely Fair Scheduler (CFS) – new hotness
- Other advanced scheduling issues
  - Real-time scheduling
  - Kernel preemption
  - Priority laundering
    - Security attack trick developed at Stony Brook

Fair Scheduling

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

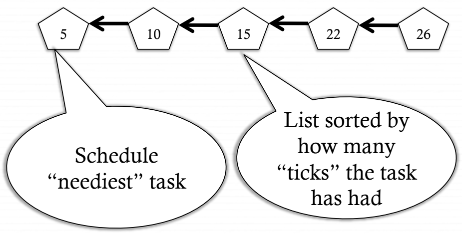
Editorial

- Real issue: O(1) scheduler bookkeeping is complicated
  - Heuristics for various issues makes it more complicated
  - Heuristics can end up working at cross-purposes
- Software engineering observation:
  - Kernel developers better understood scheduling issues and workload characteristics, could make more informed design choice
- Elegance: Structure (and complexity) of solution matches problem

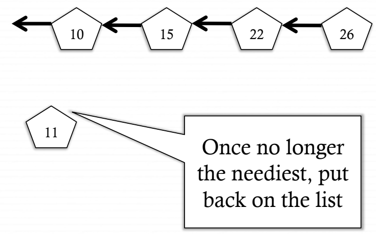
CFS idea

- 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



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

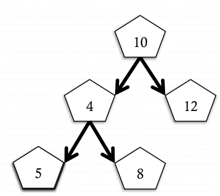
- Global virtual clock: ticks at a fraction of real time
  - Fraction is number of total tasks
- Each task counts how many clock ticks it has had
- Example: 4 tasks
  - Global vclock ticks once every 4 real ticks
  - Each task scheduled for one real tick; advances local clock by one tick

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 (more realistic)

Global Ticks: 13



- 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

Edge case 1

- 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

What happened to priorities?

- Priorities let me be delibe
  - This is a useful feature
- In CFS, priorities weigh t
- 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

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

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

- 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

- Per group or user scheduling
  - Real to virtual tick ratio becomes a function of number of both global and user's/group's tasks
- Unclear how CPU topologies are addressed

Recap: Ticks galore!

- Real time is measured by a timer device, which "ticks" at a certain frequency by raising a timer interrupt
- A process's virtual tick is some number of real ticks
  - We implement priorities, per-user fairness, etc. by tuning this ratio
- The global tick counter is used to keep track of the maximum possible virtual ticks a process has had.
  - Used to calculate one's deficit

CFS Summary

- Simple idea: logically a queue of runnable tasks, ordered by who has had the least CPU time
- Implemented with a tree for fast lookup, reinsertion
- Global clock counts virtual ticks
- Priorities and other features/tweaks implemented by playing games with length of a virtual tick
  - Virtual ticks vary in wall-clock length per-process

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 file system data gets evicted
  - Optional reading (interesting): Nemesis – an OS without shared caches to improve real-time scheduling

Simple hack

- Create a highest-priority scheduling class for real-time process
  - 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
- Assumption: like GUI programs, RR tasks will spend most of their time blocked on I/O
  - Latency is key concern

Next issue: 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

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 that assumes it won't be interrupted
- General strategy: allow fragile code to disable preemption
  - Cf: 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

Priority Laundering

- Some attacks are based on race conditions for OS resources (e.g., symbolic links)
  - Generally, these are privilege-escalation attacks against administrative utilities (e.g., passwd)
- Can only be exploited if attacker controls scheduling
  - Ensure that victim is descheduled after a given system call (not explained today)
  - Ensure that attacker always gets to run after the victim

Problem rephrased

- At some arbitrary point in the future, I want to be sure task X is at the front of the scheduler queue
  - But no sooner
  - And I have some CPU-intensive work I also need to do
- Suggestions?

Dump work on your kids

- Strategy:
  - Create a child process to do all the work
    - And a pipe
  - Parent attacker spends all of its time blocked on the pipe
    - Looks I/O bound – gets priority boost!
  - Just before right point in the attack, child puts a byte in the pipe
    - Parent uses short sleep intervals for fine-grained timing
  - Parent stays at the front of the scheduler queue

SBU Pride

- This trick was developed as part of a larger work on exploiting race conditions at SBU
  - By Rob Johnson and SPLAT lab students
  - An optional reading, if you are interested
- Something for the old tool box…

Summary

- Understand:
  - Completely Fair Scheduler (CFS)
  - Real-time scheduling issues
  - Kernel preemption
  - Priority laundering