Scheduling II

- Multilevel queue scheduling
- Multiprocessor scheduling issues
- Real-time scheduling
- Linux scheduling

Motivation

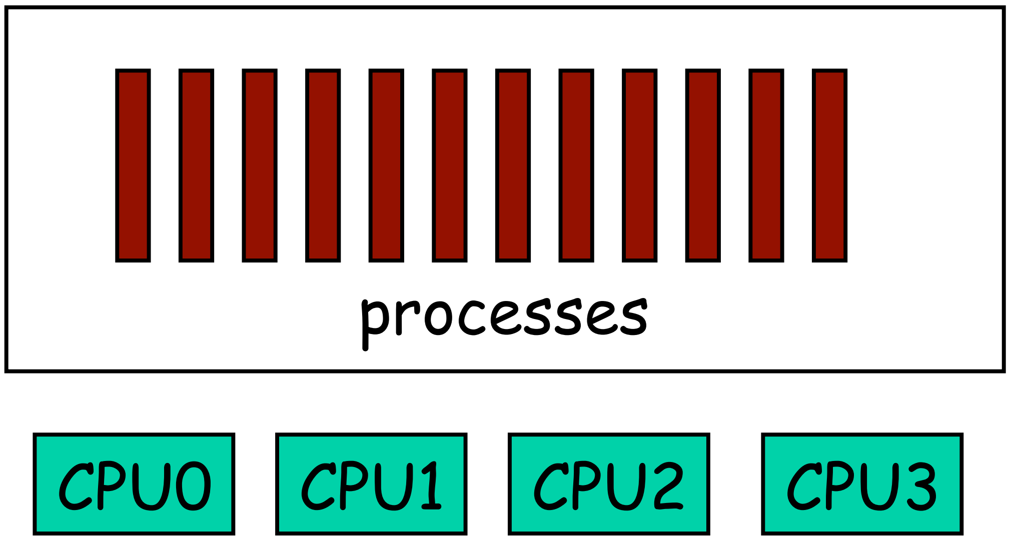
- No one-size-fits-all scheduler
  - Different workloads
  - Different environment
- Building a general scheduler that works well for all is difficult!
- Real scheduling algorithms are often more complex than the simple scheduling algorithms we've seen so far

Combining scheduling algorithms

- Multilevel queue scheduling: ready queue is partitioned into multiple queues
- Each queue has its own scheduling algorithm
  - Foreground processes: RR
  - Background processes: FCFS
- Must choose scheduling algorithm to schedule between queues. Possible algorithms
  - RR between queues
  - Fixed priority for each queue

Multiprocessor scheduling issues

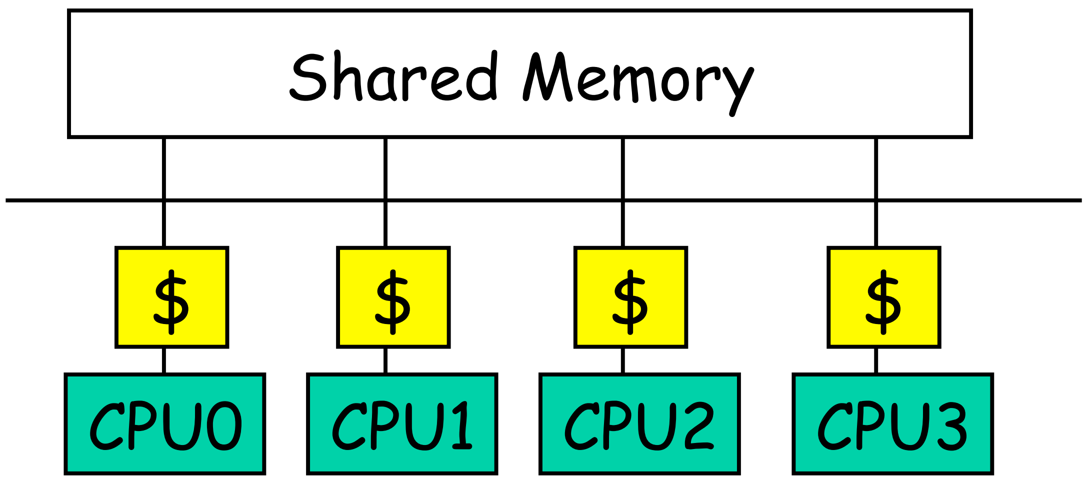
- Shared-memory Multiprocessor



- How to allocate processes to CPU?

Symmetric multiprocessor

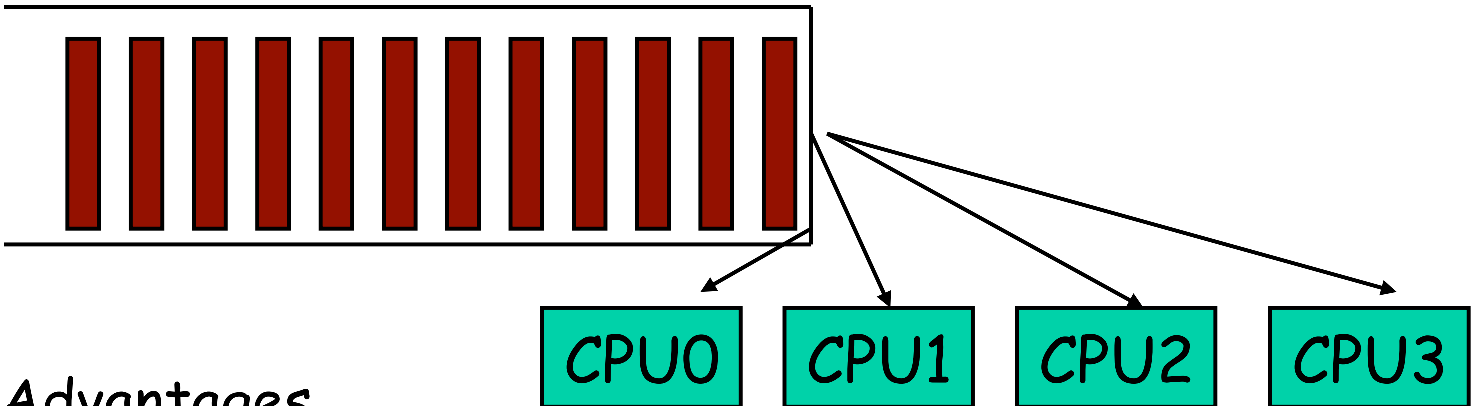
- Architecture



- Small number of CPUs
- Same access time to main memory
- Private cache

Global queue of processes

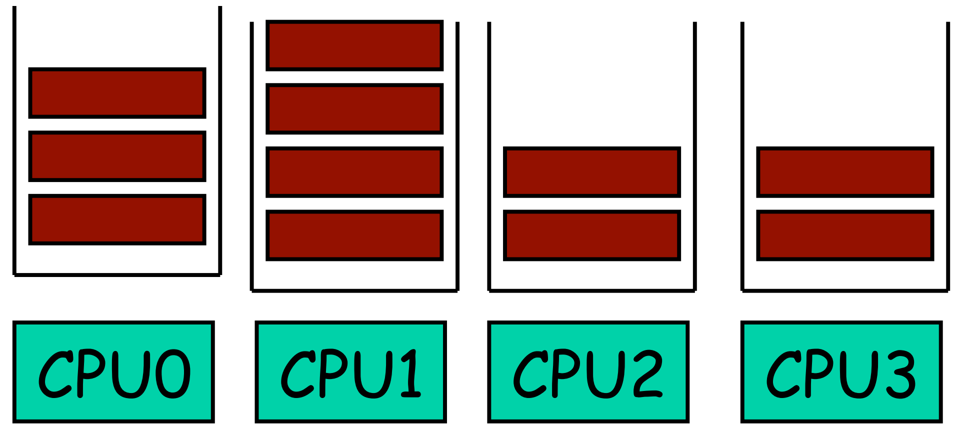
- One ready queue shared across all CPUs



- Advantages
  - Good CPU utilization
  - Fair to all processes
- Disadvantages
  - Not scalable (contention for global queue lock)
  - Poor cache locality
- Linux 2.4 uses global queue

Per-CPU queue of processes

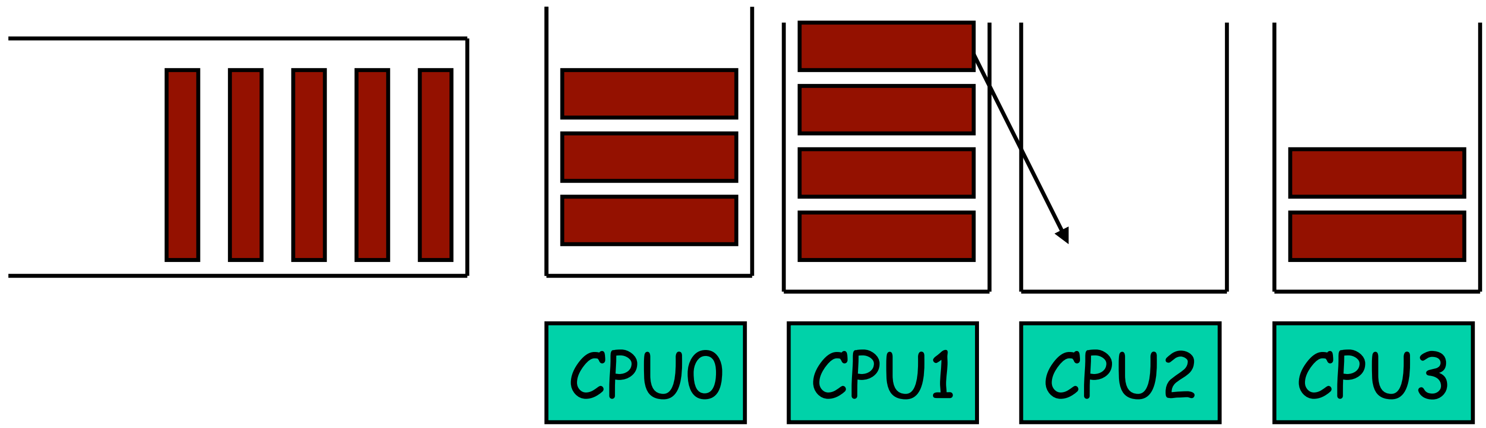
- Static partition of processes to CPUs



- Advantages
  - Easy to implement
  - Scalable (no contention on ready queue)
  - Better cache locality
- Disadvantages
  - Load-imbalance (some CPUs have more processes)
    - Unfair to processes and lower CPU utilization

Hybrid approach

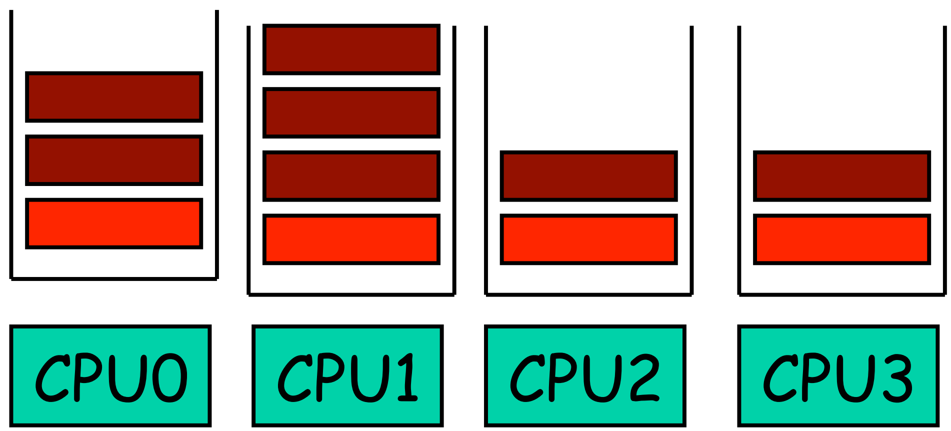
- Use both global and per-CPU queues
- Balance jobs across queues



- Processor Affinity
  - *Add process to a CPU's queue if recently run on the CPU*
    - Cache state may still present
- Linux 2.6 uses a very similar approach

SMP: "gang" scheduling

- Multiple processes need coordination
- Should be scheduled simultaneously



- Scheduler on each CPU does not act independently
- Coscheduling (gang scheduling): run a set of processes simultaneously
- Global context-switch across all CPUs

Real-time scheduling

- Real-time processes have timing constraints
  - Expressed as deadlines or rate requirements
  - E.g., gaming, video/music player, autopilot…
- Hard real-time systems – required to complete a critical task within a guaranteed amount of time
- Soft real-time computing – requires that critical processes receive priority over less fortunate ones
- Linux supports soft real-time

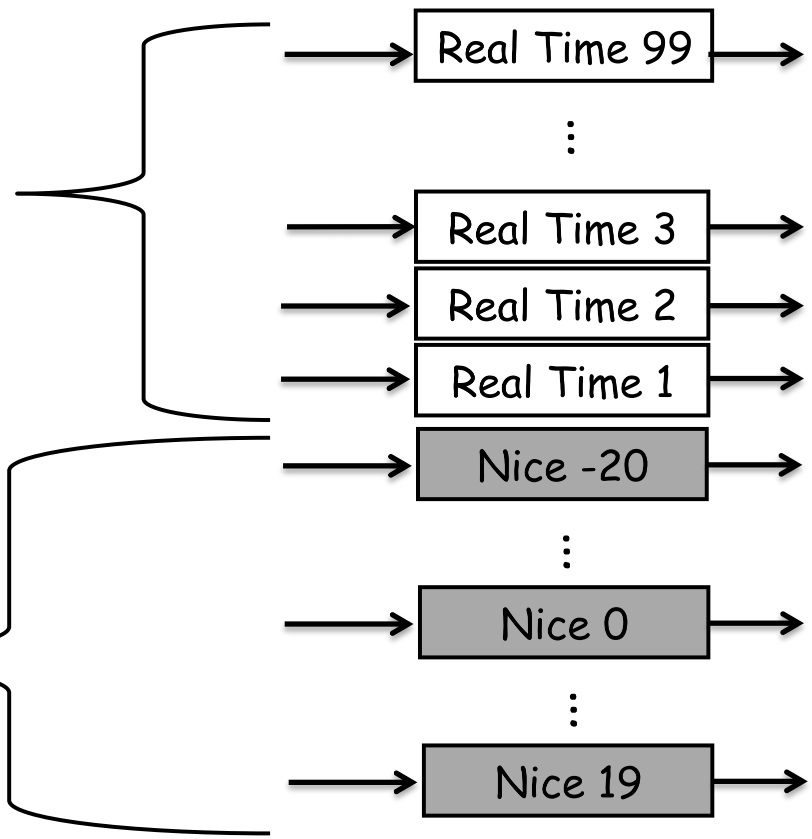
Linux scheduling overview

- Multilevel Queue Scheduler
  - Each queue associated with a priority
  - Some processes' priorities may be adjusted dynamically

- Two classes of processes
  - Soft real-time processes: always schedule highest priority processes
    - FCFS (SCHED_FIFO) or RR (SCHED_RR) for processes with same priority
  - Normal processes: priority with aging
    - RR for processes with same priority (SCHED_NORMAL)

Linux scheduling priorities

- Soft real-time scheduling policies
  - SCHED_FIFO (FCFS)
  - SCHED_RR (round robin)
  - Priority over normal tasks
  - 100 static priority levels (1..99)
- Normal scheduling policies
  - SCHED_NORMAL: standard
    - SCHED_OTHER in POSIX
  - SCHED_BATCH: CPU bound
  - SCHED_IDLE: lower priority
  - Static priority is 0
    - 40 dynamic priority
    - "Nice" values
- sched_setscheduler(), nice()
  - See man page for detailed description



Linux scheduler implementations

- Linux 2.4: global queue, O(N)
  - Simple
  - Poor performance on multiprocessor/core
  - Poor performance when n is large
- Linux 2.5: O(1) scheduler, per-CPU run queue
  - Solves performance problems in the old scheduler
  - Complex, error prone logic to boost interactivity
  - No guarantee of fairness
- Linux 2.6: completely fair scheduler (CFS)
  - Fair
  - Naturally boosts interactivity

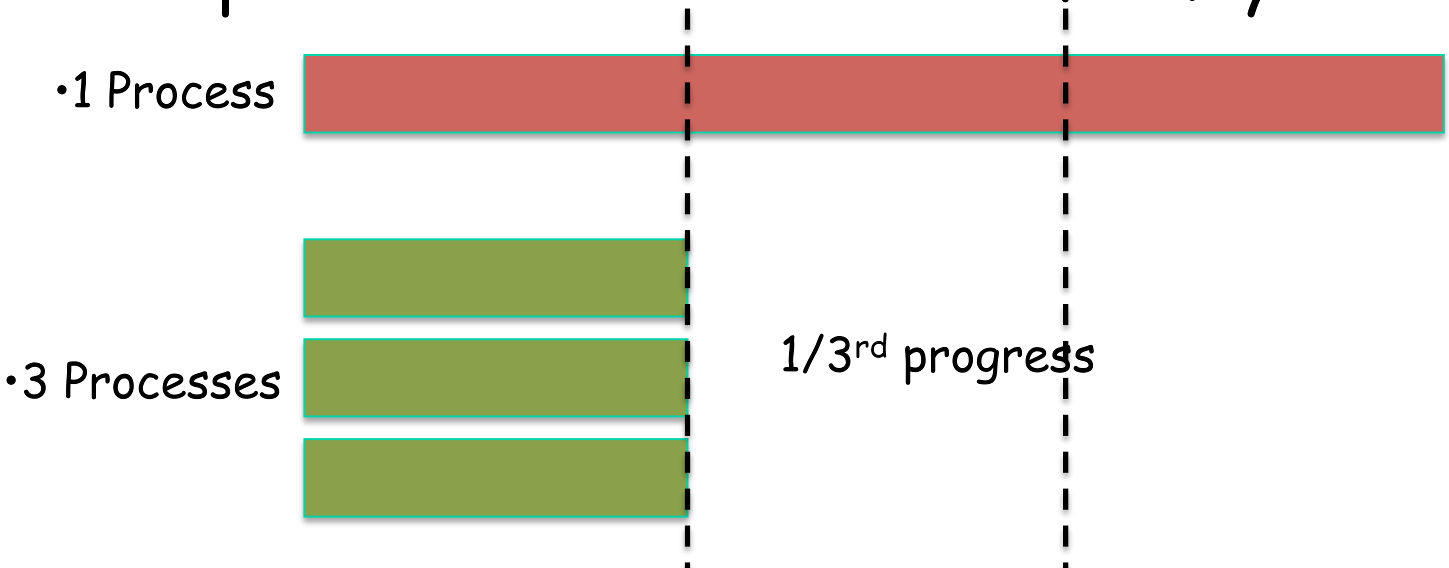
Problems with O(1) scheduler

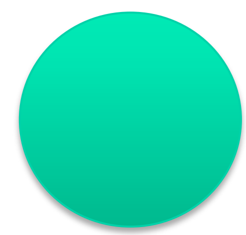
- Priorities for interactive processes?
  - Higher priorities than CPU-bound processes
  - How to detect interactive processes?
  - Heuristics: more sleep/wait time ➔ more interactive ➔ higher dynamic priorities
  - Ad hoc, can be unfair

- Fairness for processes with diff. priorities?
  - Convert priority to time slice
  - Higher priorities get bigger time slices
  - Aging for low-priority processes
  - Ad hoc, can be unfair

Ideal fair scheduling

- Infinitesimally small time slice
- n processes: each runs uniformly at $1/n^{th}$ rate





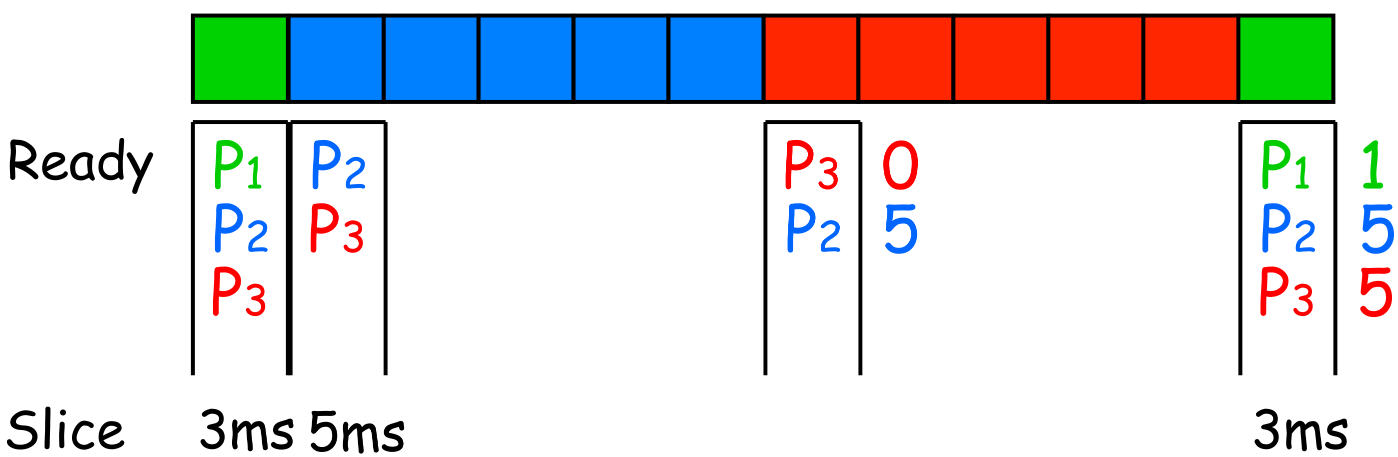
- "Ideal multitasking CPU"
- Weighted fair scheduling
- Fair queuing [John Nagle 1985], stride scheduling [Carl A. Waldspurger, 1995]

Completely Fair Scheduler (CFS)

- Approximate fair scheduling
  - Run each process once per schedule latency period
    - sysctl_sched_latency
  - Time slice for process Pi: T * Wi/(Sum of all Wi)
    - sched_slice()
- Too many processes?
  - Lower bound on smallest time slice
  - Schedule latency = lower bound * number of procs
- Introduced in Linux 2.6.23

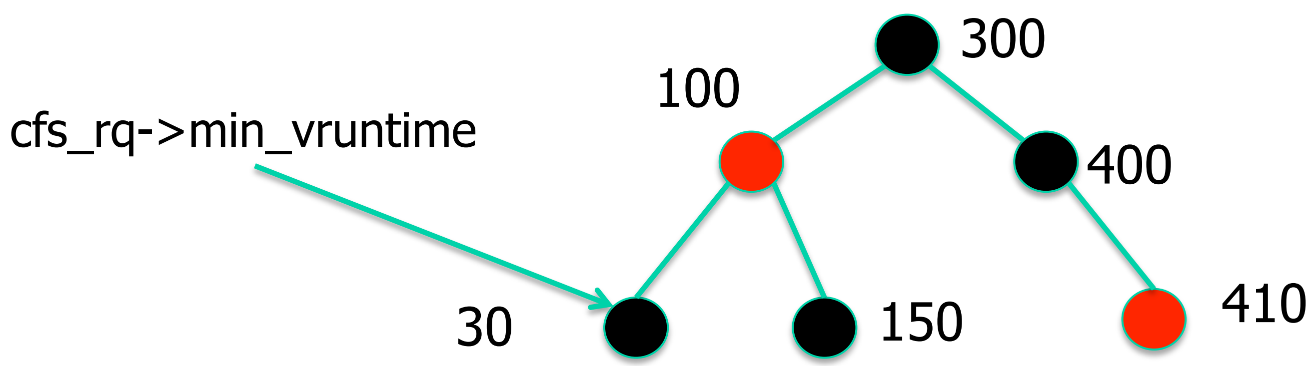
Picking the next process

- Pick proc with weighted minimum runtime so far
  - Virtual runtime: task->vruntime += executed time / Wi
- Example
  - P1: 1 ms burst per 10 ms (schedule latency)
  - P2 and P3 are CPU-bound
  - All processes have the same weight (1)



Finding proc with minimum runtime fast

- Red-black tree
  - Balanced binary search tree
  - Ordered by vruntime as key
  - O(lgN) insertion, deletion, update, O(1): find min



- Tasks move from left of tree to the right
- min_vruntime caches smallest value
- Update vruntime and min_vruntime
  - When task is added or removed
  - On every timer tick, context switch

Converting nice level to weight

- Table of nice level to weight
  - static const int prio_to_weight[40] (kernel/sched/sched.h)
- Nice level changes by 1 ➔ 10% weight

- Pre-computed to avoid
  - Floating point operations
  - Runtime overhead

Fsck all that...

Enter BFS

The scheduler that shall not be named

Backup slides

Hierarchical, modular scheduler

- Code from kernel/sched/core.c:

```
class = sched_class_highest;
for ( ; ; ) {
        p = class->pick_next_task(rq);
        if (p)
                return p;
        /*
         * Will never be NULL as the idle class always
         * returns a non-NULL p:
         */
        class = class->next;
}
```

sched_class Structure

```
static const struct sched_class fair_sched_class = {
        .next                   = &idle_sched_class,
        .enqueue_task           = enqueue_task_fair,
        .dequeue_task           = dequeue_task_fair,
        .yield_task             = yield_task_fair,
        .check_preempt_curr     = check_preempt_wakeup,
        .pick_next_task         = pick_next_task_fair,
        .put_prev_task          = put_prev_task_fair,
        .select_task_rq         = select_task_rq_fair,
        .load_balance           = load_balance_fair,
        .move_one_task          = move_one_task_fair,
        .set_curr_task          = set_curr_task_fair,
        .task_tick              = task_tick_fair,
        .task_fork              = task_fork_fair,
        .prio_changed           = prio_changed_fair,
        .switched_to            = switched_to_fair,
}
```

The runqueue

- All run queues available in array runqueues, one per CPU
- struct rq (kernel/sched/sched.h)
  - Contains per-class run queues (RT, CFS) and params
    - E.g., CFS: a red-black tree of task_struct (struct rb_root tasks_timeline)
    - E.g., RT: array of active priorities
    - Data structure rt_rq, cfs_rq,
- struct sched_entity (include/linux/sched.h)
  - Member of task_struct, one per scheduler class
  - Maintains struct rb_node run_node, other per-task params
- Current scheduler for task is specified by task_struct.sched_class
  - Pointer to struct sched_class
  - Contains functions pertaining to class (object-oriented code)

Adding a new Scheduler Class

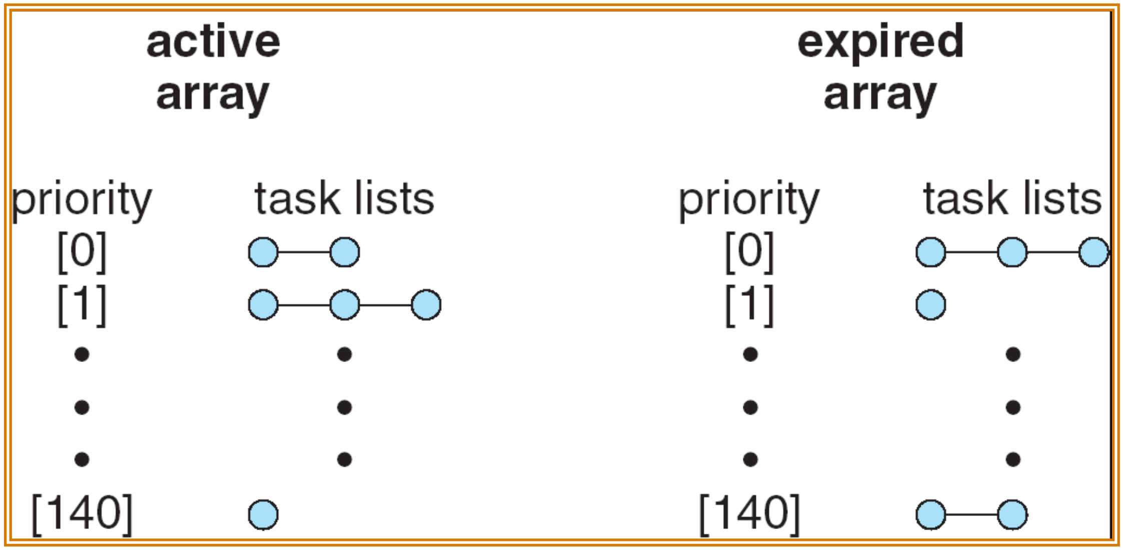
- The Scheduler is modular and extensible
  - New scheduler classes can be installed
  - Each scheduler class has priority within hierarchical scheduling hierarchy
  - Linked list of sched_class sched_class.next reflects priority
  - Core functions: kernel/sched/core.c, kernel/sched/sched.h, include/linux/sched.h
  - Additional classes: kernel/sched/fair.c, rt.c
- Process changes class via sched_setscheduler syscall
- Each class needs
  - New runqueue structure in main struct rq
  - New sched_class structure implementing scheduling functions
  - New sched_entity in the task_struct

Linux O(1) scheduler goals

- Avoid starvation
- Boost interactivity
  - Fast response to user despite high load
  - Achieved by inferring interactive processes and dynamically increasing their priorities
- Scale well with number of processes
  - O(1) scheduling overhead
- SMP goals
  - Scale well with number of processors
  - Load balance: no CPU should be idle if there is work
  - CPU affinity: no random bouncing of processes
- Reference: Linux/Documentation/sched-design.txt

runqueue data structure

- Two arrays of priority queues
  - active and expired
  - Total 140 priorities [0, 140)
  - Smaller integer = higher priority



Scheduling algorithm for normal processes

1. Find highest priority non-empty queue in rq->active; if none, simulate aging by swapping active and expired
2. next = first process on that queue
3. Adjust next's priority
4. Context switch to next
5. When next used up its time slice, insert next to the right queue the expired array and call schedule() again

Aging: the traditional algorithm

```
for(pp = proc; pp < proc+NPROC; pp++) {
        if (pp->prio != MAX)
                pp->prio++;
        if (pp->prio > curproc->prio)
                reschedule();
}
```

Problem: O(N). Every process is examined on each schedule() call!

This code is taken almost verbatim from 6th Edition Unix, circa 1976.

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Simulate aging

- Swapping active and expired gives low priority processes a chance to run

- Advantage: O(1)
  - Processes are touched only when they start or stop running

Find highest priority non-empty queue

- Time complexity: O(1)
  - Depends on the number of priority levels, not the number of processes
- Implementation: a bitmap for fast look up
  - 140 queues → 5 integers
  - A few compares to find the first non-zero bit
  - Hardware instruction to find the first 1-bit
    - bsfl on Intel

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 it blocks or yields voluntarily
  - RR within same priority level
- Round-robin: SCHED_RR
  - As above but with a time quanta
- Normal processes have SCHED_NORMAL scheduling policy

Multiprocessor scheduling

- Per-CPU runqueue
- Possible for one processor to be idle while others have jobs waiting in their run queues
- Periodically, rebalance runqueues
  - Migration threads move processes from one runque to another
- The kernel always locks runqueues in the same order for deadlock prevention

Adjusting priority

- Goal: dynamically increase priority of interactive process
- How to determine interactive?
  - Sleep ratio
  - Mostly sleeping: I/O bound
  - Mostly running: CPU bound
- Implementation: per process sleep_avg
  - Before switching out a process, subtract from sleep_avg how many ticks a task ran
  - Before switching in a process, add to sleep_avg how many ticks it was blocked up to MAX_SLEEP_AVG (10 ms)

Calculating time slices

- Stored in field time_slice in struct task_struct
- Higher priority processes also get bigger time-slice
- task_timeslice() in sched.c
  - If (static_priority < 120) time_slice = (140-static_priority) * 20
  - If (static_priority >= 120) time_slice = (140-static_priority) * 5

Example time slices

Priority:	Static Pri	Niceness	Quantum
Highest	100	-20	800 ms
High	110	-10	600 ms
Normal	120	0	100 ms
Low	130	10	50 ms
Lowest	139	20	5 ms

Priority partition

- Total 140 priorities [0, 140)
  - Smaller integer = higher priority
  - Real-time: [0,100)
  - Normal: [100, 140)

- MAX_PRIO and MAX_RT_PRIO
  - include/linux/sched.h

Priority related fields in *struct task_struct*

- static_prio: static priority set by administrator/users
  - Default: 120 (even for realtime processes)
  - Set use sys_nice() or sys_setpriority()
    - Both call set_user_nice()
- prio: dynamic priority
  - Index to prio_array
- rt_priority: real time priority
  - prio = 99 - rt_priority
- include/linux/sched.h

Outline

- Advanced scheduling issues
  - Multilevel queue scheduling
  - Multiprocessor scheduling issues
  - Real-time scheduling

- Scheduling in Linux
  - Scheduling algorithm
  - Setting priorities and time slices
  - Other implementation issues

Bookkeeping on each timer interrupt

- scheduler_tick()
  - Called on each tick
    - timer_interrupt ➔ do_timer_interrupt ➔ do_timer_interrupt_hook ➔ update_process_times
- If realtime and SCHED_FIFO, do nothing
  - SCHED_FIFO is non-preemptive
- If realtime and SCHED_RR and used up time slice, move to end of rq->active[prio]
- If SCHED_NORMAL and used up time slice
  - If not interactive or starving expired queue, move to end of rq->expired[prio]
  - Otherwise, move to end of rq->active[prio]
    - Boost interactive
- Else // SCHED_NORMAL, and not used up time slice
  - Break large time slice into pieces TIMESLICE_GRANULARITY

Processor affinity

- Each process has a bitmask saying what CPUs it can run on
  - By default, all CPUs
  - Processes can change the mask
  - Inherited by child processes (and threads), thus tending to keep them on the same CPU
- Rebalancing does not override affinity

Load balancing

- To keep all CPUs busy, load balancing pulls tasks from busy runqueues to idle runqueues.
- If *schedule* finds that a runqueue has no runnable tasks (other than the idle task), it calls *load_balance*
- *load_balance* also called via timer
  - *schedule_tick* calls *rebalance_tick*
  - Every tick when system is idle
  - Every 100 ms otherwise

Load balancing (cont.)

- *load_balance* looks for the busiest runqueue (most runnable tasks) and takes a task that is (in order of preference):
  - inactive (likely to be cache cold)
  - high priority
- *load_balance* skips tasks that are:
  - likely to be cache warm (hasn't run for *cache_decay_ticks* time)
  - currently running on a CPU
  - not allowed to run on the current CPU (as indicated by the *cpus_allowed* bitmask in the *task_struct*)

Optimizations

- If next is a kernel thread, borrow the MM mappings from prev
  - User-level MMs are unused.
  - Kernel-level MMs are the same for all kernel threads
- If prev == next
  - Don't context switch

CFS: Scheduling Latency

- Equivalent to time slice across all processes
  - Approximation of infinitesimally small
  - To set/get type: $ sysctl kernel.sched_latency_ns
- Each process gets equal proportion of slice
  - Timeslice(task) = latency/nr_tasks
  - Lower bound on smallest slice
  - To set/get: $ sysctl kernel.sched_min_granularity_ns
  - Too many tasks? sched_latency = nr_tasks*min_granularity
- Priority through proportional sharing
  - Task gets share of CPU proportional to relative priority
  - Timeslice(task) = Timeslice(t) * prio(t) / Sum_all_t'(prio(t'))
- Maximum wait time bounded by scheduling latency

CFS: Picking the Next Process

- Pick task with minimum runtime so far
  - Tracked by vruntime member variable
  - Every time process runs for t ns, vruntime +=t (weighed by process priority)
- How does this impact I/O vs CPU bound tasks
  - Task A: needs 1 msec every 100 sec (I/O bound)
  - Task B, C: 80 msec every 100 msec (CPU bound)
  - After 10 times that A, B, and C have been scheduled
    - vruntime(A) = 10, vruntime(B, C) = 800
    - A gets priority, B and C get large time slices (10msec each)
- Problem: how to efficiently track min runtime?
  - Scheduler needs to be efficient
  - Finding min every time is an O(N) operation