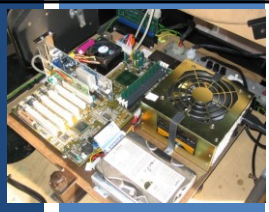
TCSS 422: OPERATING SYSTEMS



Proportional Share Schedulers, Linux Completely Fair Scheduler, Introduction to Concurrency

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

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TEXT BOOK COUPON

- 15% off textbook code: **AAC72SAVE15**
- https://www.lulu.com/shop/andrea-arpaci-dusseau-and-remzi-arpaci-dusseau/operating-systems-three-easy-pieces-hardcover-version-110/hardcover/product-15gjeeky.html?q=three+easy+pieces+operating+systems&page=1&pageSize=4
- With coupon textbook is only $33.79 + tax & shipping

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TCSS 422 – OFFICE HRS – SPRING 2025

- Office Hours plan for Winter:
- Tuesday 2:30 - 3:30 pm Instructor Wes, Zoom
- Tue/Thur 6:00 - 7:00 pm Instructor Wes, CP 229/Zoom
- Tue 6:00 – 7:00 pm GTA Robert, Zoom/MDS 302
- Wed 1:00 – 2:00 pm GTA Robert, Zoom/MDS 302

- Instructor is available after class at 6pm in CP 229 each day

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OBJECTIVES – 2/3

- Questions from 1/29
- C Tutorial - Pointers, Strings, Exec in C - Due Wed Feb 11 AOE
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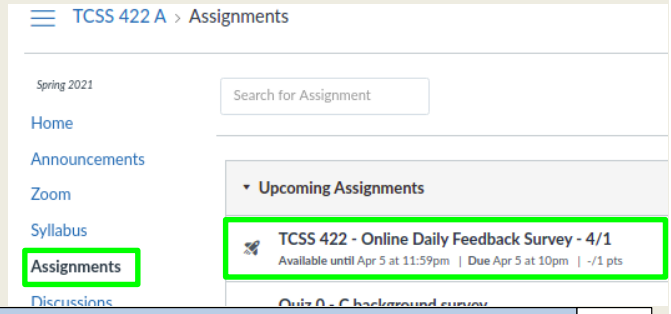
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 11:59p
- Thursday surveys: due ~ Mon @ 11:59p



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TCSS 422 - Online Daily Feedback Survey - 4/1

Quiz Instructions

Question 1 0.5 pts

On a scale of 1 to 10, please classify your perspective on material covered in today's class:

1	2	3	4	5	6	7	8	9	10
Mostly Review To Me				Equal New and Review					Mostly New to Me

Question 2 0.5 pts

Please rate the pace of today's class:

1	2	3	4	5	6	7	8	9	10
Slow				Just Right					Fast

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (41 of 46 respondents – 89.1%) :
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 5.75 (↓ - previous 7.00)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.03 (↓ - previous 5.59)**

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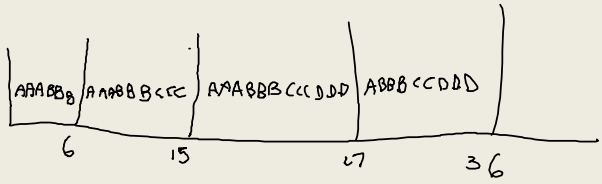
Q2



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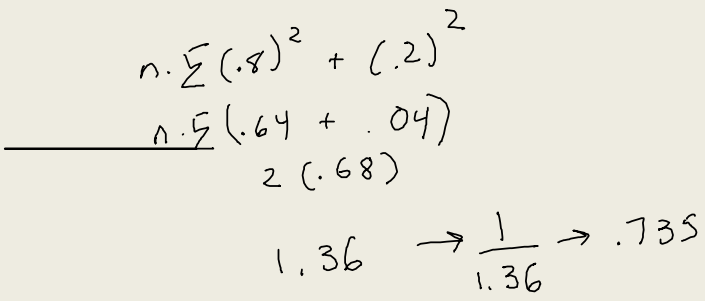

$$\frac{n \cdot \sum (.8)^2 + (.2)^2}{n \cdot \sum (.64 + .04)}$$

$$2(.68)$$

$$1.36 \rightarrow \frac{1}{1.36} \rightarrow .735$$

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FEEDBACK FROM 1/29

- ***Do argv I/O errors exist?***

- In: `int main(int argc, char * argv[])`
- `argv[]` is an array of pointers to C strings
- Reading elements of the `argv[]` array, reads memory
- No I/O is performed
- No reads, writes, syscalls
- There should be no I/O errors

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FEEDBACK FROM 4/22

- ***What would happen in an MLFQ scheduler if there are so many jobs overall that the high priority queue never finishes giving each job a time slice to execute before doing a priority boost?***
- cycle time – total time shared among all jobs in a run queue
- time slice – time an individual job runs for
- From slide 6.50:
  - no rule explicitly describes how the cycle time is divided among jobs
  - No rule explicitly describes how time slice is determine
- Any MLFQ problem having this issue would require rules to describe how this scenario is handled to allow a scheduling graph to be drawn

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REVIEW: MLFQ RULE SUMMARY

- The refined set of MLFQ rules:
- **Rule 1:** If Priority(A) > Priority(B), A runs (B doesn't).
- **Rule 2:** If Priority(A) = Priority(B), A & B run in RR.
- **Rule 3:** When a job enters the system, it is placed at the highest priority.
- **Rule 4:** Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced(i.e., it moves down on queue).
- **Rule 5:** After some time period S, move all the jobs in the system to the topmost queue.

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ADDRESSING AN OVERLOADED RUNQUEUE

- One possible way:
  - Cycle time split evenly among jobs in runqueue with no min timeslice
  - For MLFQ, all jobs in runqueue use full timeslice and have priority reduced
  - Not realistic in practice - timeslice becomes too small to be useful
- Another way:
  - Specify min_time_slice (1 ms) per job, and total_cycle_time (10 ms)
  - Job's time_slice = total_cycle_time / jobs_in_runqueue
  - Beyond 10 jobs, other jobs receive no runtime this cycle
  - Jobs receiving no runtime are scheduled first in next cycle
  - Jobs could pile up and experience multi-cycle delays
  - More realistic

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ASSIGNMENT 0 - CLOSES TUE FEB 03 AOE

- Due Friday Jan 30 AOE (Jan 31 @ 4:59am)
- Grace period: submission ok until Mon Feb 2 @ 4:59 AM
- Late submissions thru Wed Feb 4 @ 4:59am

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QUIZ 1

- Active reading on Chapter 9 – Proportional Share Schedulers
- Posted in Canvas
- Due Wednesday Feb 4th AOE
- **Link:**
- **https://faculty.washington.edu/wlloyd/courses/tcss422/quiz/TCSS422_w2026_quiz_1.pdf**

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QUIZ 2

- Canvas Quiz – Practice CPU Scheduling Problems
- Posted in Canvas
- Unlimited attempts
- Due Tuesday Feb 10th AOE (Feb 11th at 4:59am)
- **Link:**
- **https://canvas.uw.edu/courses/1871290/assignments/11129208**

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CHAPTER 9 - PROPORTIONAL SHARE SCHEDULER

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OBJECTIVES – 2/3

- Chapter 9: Proportional Share Schedulers
  - Lottery scheduler
  - Ticket mechanisms
  - Stride scheduler
  - Linux Completely Fair Scheduler

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PROPORTIONAL SHARE SCHEDULER

- Also called fair-share scheduler or lottery scheduler
  - Guarantees each job receives some percentage of CPU time based on share of "tickets"
  - Each job receives an allotment of tickets
  - % of tickets corresponds to potential share of a resource
  - Can conceptually schedule any resource this way
    - CPU, disk I/O, memory

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LOTTERY SCHEDULER

- Simple implementation
  - Just need a random number generator
    - Picks the winning ticket
  - Maintain a data structure of jobs and tickets (list)
  - Traverse list to find the owner of the ticket
  - Consider sorting the list for speed

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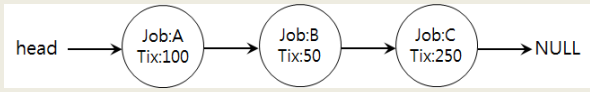
LOTTERY SCHEDULER IMPLEMENTATION




```
1         // counter: used to track if we've found the winner yet
2         int counter = 0;
3
4         // winner: use some call to a random number generator to
5         // get a value, between 0 and the total # of tickets
6         int winner = getrandom(0, totaltickets);
7
8         // current: use this to walk through the list of jobs
9         node_t *current = head;
10
11        // loop until the sum of ticket values is > the winner
12        while (current) {
13                  counter = counter + current->tickets;
14                  if (counter > winner)
15                            break; // found the winner
16                  current = current->next;
17        }
18        // 'current' is the winner: schedule it...
```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OBJECTIVES – 2/3

- Chapter 9: Proportional Share Schedulers
  - Lottery scheduler
  - **Ticket mechanisms**
  - Stride scheduler
  - Linux Completely Fair Scheduler

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TICKET MECHANISMS

- Ticket currency / exchange
  - User allocates tickets in any desired way
  - OS converts user currency into global currency
- Example:
  - There are 200 global tickets assigned by the OS

User A → *500* (A's currency) to A1 → *50* (global currency)
→ *500* (A's currency) to A2 → *50* (global currency)

User B → *10* (B's currency) to B1 → *100* (global currency)

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TICKET MECHANISMS - 2

- Ticket transfer
  - Temporarily hand off tickets to another process
- Ticket inflation
  - Process can temporarily raise or lower the number of tickets it owns
  - If a process needs more CPU time, it can boost tickets.

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LOTTERY SCHEDULING

- Scheduler picks a **winning** ticket
  - Load the job with the winning ticket and run it
- Example:
  - Given 100 tickets in the pool
    - Job A has 75 tickets: 0 - 74
    - Job B has 25 tickets: 75 – 99

Scheduler's winning tickets:	63	85	70	39	76	17	29	41	36	39	10	99	68	83	63
Scheduled job:	A	B	A	A	B	A	A	A	A	A	A	B	A	B	A

- But what do we know about probability of a coin flip?

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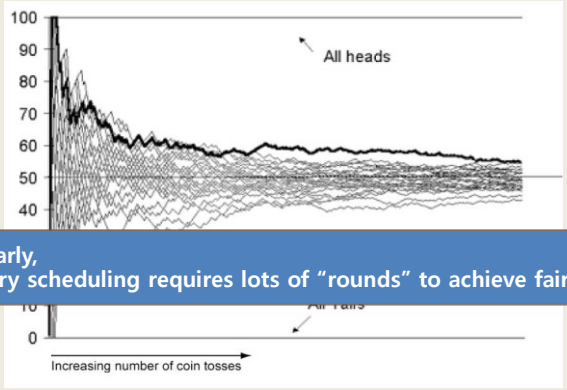
COIN FLIPPING

- Equality of distribution (fairness) requires a lot of flips!



Similarly,
Lottery scheduling requires lots of "rounds" to achieve fairness.

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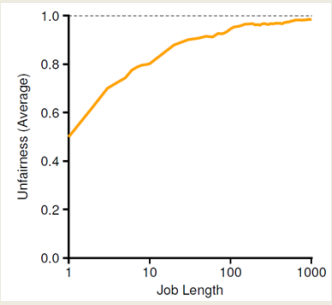
LOTTERY FAIRNESS

- With two jobs
  - Each with the same number of tickets (t=100)



When the job length is not very long,
average unfairness can be **quite severe**.

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LOTTERY SCHEDULING CHALLENGES

- What is the best approach to assign tickets to jobs?
  - Typical approach is to assume users know best
  - Users are provided with tickets, which they allocate as desired
- How should the OS automatically distribute tickets upon job arrival?
  - What do we know about incoming jobs a priori ?
  - Ticket assignment is really an open problem…

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WE WILL RETURN AT 5:00PM

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OBJECTIVES – 2/3

- Chapter 9: Proportional Share Schedulers
  - Lottery scheduler
  - Ticket mechanisms
  - **Stride scheduler**
  - Linux Completely Fair Scheduler

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STRIDE SCHEDULER

- Addresses statistical probability issues with lottery scheduling
- Instead of guessing a random number to select a job, simply count…

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STRIDE SCHEDULER - 2

- Jobs have a "stride" value
  - A stride value describes the counter pace when the job should give up the CPU
  - Stride value is **inverse in proportion** to the job's number of tickets (more tickets = smaller stride)
- Total system tickets = 10,000
  - Job A has 100 tickets → A_{stride} = 10000/100 = 100 stride
  - Job B has 50 tickets → B_{stride} = 10000/50 = 200 stride
  - Job C has 250 tickets → C_{stride} = 10000/250 = 40 stride
- Stride scheduler tracks "pass" values for each job (A, B, C)

STRIDE SCHEDULER - 3

- Basic algorithm:
  1. Stride scheduler picks job with the lowest pass value
  2. Scheduler increments job's pass value by its stride and starts running
  3. Stride scheduler increments a counter
  4. When counter exceeds pass value of current job, pick a new job (go to 1)
- KEY: When the counter reaches a job's "PASS" value, the scheduler passes on to the next job…

STRIDE SCHEDULER - EXAMPLE

- Stride values
  - Tickets = priority to select job
  - Stride is inverse to tickets
  - Lower stride = more chances to run (higher priority)

Priority

C stride = 40

A stride = 100

B stride = 200

40

STRIDE SCHEDULER EXAMPLE - 2

- Three-way tie: randomly pick job A (all pass values=0)
- Set A's pass value to A's stride = 100
- Increment counter until > 100
- Pick a new job: two-way tie

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	...

Tickets
C = 250
A = 100
B = 50

Initial job selection is random. All @ 0

C has the most tickets and receives a lot of opportunities to run…

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STRIDE SCHEDULER EXAMPLE - 3

- We set A's counter (pass value) to A's stride = 100
- Next scheduling decision between B (pass=0) and C (pass=0)
  - Randomly choose B
- C has the lowest counter for next 3 rounds

Tickets
C = 250
A = 100
B = 50

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	...

C has the most tickets and is selected to run more often …

STRIDE SCHEDULER EXAMPLE - 4

- Job counters support determining which job to run next
- Over time jobs are scheduled to run based on their priority represented as their **share of tickets…**
- **Tickets are analogous to job priority**

Tickets
C = 250
A = 100
B = 50

Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	...

Which of the following is NOT a problem with proportional share schedulers?

- A: How tickets should be distributed to incoming jobs
- B: Lottery scheduler is only eventually fair
- C: Given 2 users A and B who both receive a 50% timeshare of the system, the runtime for User A's jobs is dependent on the runtime of User B's.
- D: All of the above
- E: None of the above

Start the presentation to see live content. For screen share software, share the entire screen by using the PollEverywhere app

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LINUX: COMPLETELY FAIR SCHEDULER (CFS)

- Large Google datacenter study: *"Profiling a Warehouse-scale Computer"* (Kanev et al.)
- Monitored 20,000 servers over 3 years
- Found 20% of CPU time spent in the Linux kernel
- 5% of CPU time spent in the CPU scheduler!
- Study highlights importance for high performance OS kernels and CPU schedulers !

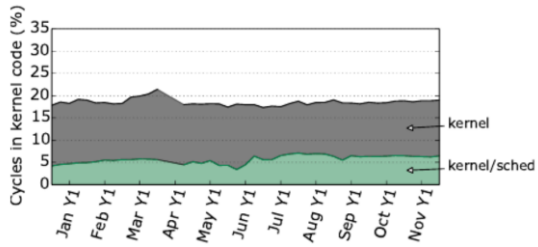

Figure 5: Kernel time, especially time spent in the scheduler, is a significant fraction of WSC cycles.

See: https://dl.acm.org/doi/pdf/10.1145/2749469.2750392

LINUX: COMPLETELY FAIR SCHEDULER (CFS)

- Loosely based on the stride scheduler
- CFS models system as a Perfect Multi-Tasking System
  - In a perfect system every process of the same priority should receive exactly $1/n^{th}$ of the CPU time
- Linux scheduling classes group jobs by priority
  - CFS only schedules user processes, those with SCHED_OTHER (SCHED_NORMAL) class (*class is also called scheduling "policy"*)
  - CFS picks task w/ lowest **`vruntime`** to run
  - Time slice varies based on how many jobs in shared runqueue
  - Minimum time slice prevents too many context switches (e.g. 3 ms)

COMPLETELY FAIR SCHEDULER - 2

- Every thread/process has a scheduling class (policy):
- **CFS classes**: SCHED_OTHER (TS), also SCHED_BATCH
  - TS = Time Sharing (most user processes have this class)
- **Real-time classes**: SCHED_FIFO (FF), SCHED_RR (RR)
- How to show scheduling class and priority:
- `#class`
  `ps -elfc`
- `#priority (nice value)`
  `ps ax -o pid,ni,cls,pri,cmd`

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COMPLETELY FAIR SCHEDULER - 3

- Linux ≥ 2.6.23: Completely Fair Scheduler (CFS)
- Linux < 2.6.23: O(1) scheduler
- Linux maintains simple counter (**vruntime**) to track how long each thread/process has run
- CFS picks user process with lowest **vruntime** to run next
- CFS adjusts timeslice based on # of proc waiting for the CPU
- Kernel parameters that specify CFS behavior:

```
$ sudo sysctl kernel.sched_latency_ns
kernel.sched_latency_ns = 24000000
$ sudo sysctl kernel.sched_min_granularity_ns
kernel.sched_min_granularity_ns = 3000000
$ sudo sysctl kernel.sched_wakeup_granularity_ns
kernel.sched_wakeup_granularity_ns = 4000000
```


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COMPLETELY FAIR SCHEDULER - 4

- **Sched_min_granularity_ns** (3ms)
  - Time slice for a process: busy system (w/ full runqueue)
  - If system has idle capacity, time slice exceeds the min as long as difference in **vruntime** between running process and process with lowest **vruntime** is less than **sched_wakeup_granularity_ns** (4ms)
- Scheduling time period is: total cycle time for iterating through a set of processes where each is allowed to run (like round robin)
- Example:
  sched_latency_ns (24ms)
  if (proc in runqueue < **sched_latency_ns**/**sched_min_granularity**)
  or
  sched_min_granularity_ns * number of processes in runqueue

Ref: https://www.systutorials.com/sched_min_granularity_ns-sched_latency_ns-cfs-affect-timeslice-processes/

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CFS TRADEOFF

- **HIGH** **sched_min_granularity_ns** (timeslice)
  sched_latency_ns
  sched_wakeup_granularity_ns

  CFS features reduced context switching → less overhead
  poor near-term fairness

- **LOW** **sched_min_granularity_ns** (timeslice)
  sched_latency_ns
  sched_wakreup_granularity_ns

  CFS features increased context switching → more overhead
  better near-term fairness

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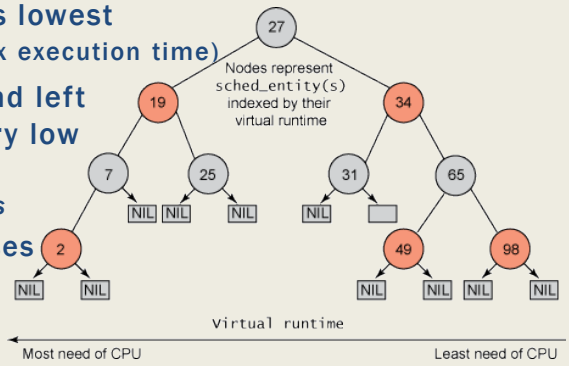
COMPLETELY FAIR SCHEDULER - 5

- Runqueues are stored using a Linux red-black tree
  - Self balancing binary tree - nodes indexed by **vruntime**
- Leftmost node has lowest **vruntime** (approx execution time)
- Walking tree to find left most node has very low big O complexity:
  ~O(log N) for N nodes
- Completed processes are removed



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LINUX: JOB NICE VALUES

- Linux ***"Nice value"***
  - Nice predates the CFS scheduler
  - Top shows nice values
  - Process command (nice & priority):
    `ps ax -o pid,ni,cmd,%cpu, pri`

```
static const int prio_to_weight[40] = {
    /* -20 */ 88761, 71755, 56483, 46273, 36291,
    /* -15 */ 29154, 23254, 18705, 14949, 11916,
    /* -10 */  9548,  7620,  6100,  4904,  3906,
    /*  -5 */  3121,  2501,  1991,  1586,  1277,
    /*   0 */  1024,   820,   655,   526,   423,
    /*   5 */   335,   272,   215,   172,   137,
    /*  10 */   110,    87,    70,    56,    45,
    /*  15 */    36,    29,    23,    18,    15,
};
```

- Nice Values: from -20 to 19
  - Lower is ***higher*** priority, default is 0
  - **vruntime** is a weighted time measurement
  - Priority weights the calculation of **vruntime** within a runqueue to give high priority jobs a ***boost***.
    - Influences job's position in rb-tree

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COMPLETELY FAIR SCHEDULER - 6

- CFS tracks cumulative job run time with the **vruntime** variable
- The task with the lowest **vruntime** is scheduled next
- **struct sched_entity** contains **vruntime** parameter
  - Describes process execution time in nanoseconds
  - Value is not pure runtime, is weighted based on job priority
  - **CFS GOAL:** Be a perfect scheduler → achieve equal **vruntime** for all processes
- Sleeping jobs: upon return a temporary **vruntime** can be used to increase temporarily the priority of the task
- When tasks wait for I/O they should receive a comparable share of the CPU as if they were performing compute ops when run again
- Key takeaway:
  identifying the next job to schedule is really fast!

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COMPLETELY FAIR SCHEDULER - 7

- More information:
- Man page: "man sched" : Describes Linux scheduling API
- http://manpages.ubuntu.com/manpages/bionic/man7/sched.7.html
- https://www.kernel.org/doc/Documentation/scheduler/sched-design-CFS.txt
- https://en.wikipedia.org/wiki/Completely_Fair_Scheduler
- See paper: The Linux Scheduler – a Decade of Wasted Cores
- http://www.ece.ubc.ca/~sasha/papers/eurosys16-final29.pdf

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BEYOND CFS → EEVDF SCHEDULER

- Earliest Eligible Virtual Deadline First (EEVDF) Scheduler
  - **Linux kernel version 6.6**, October 29, 2023
  - First described in a research article in 1995
- Like CFS, EEVDF aims to distribute CPU time equally among all runnable tasks with the same priority.
- EEVDF calculates a virtual deadline (VD) for each task, by considering each task's "lag" value – the difference between the time a task should have received vs. what it actually received.
  - Only tasks with positive lag can run. They are owed CPU time
  - A task with negative lag has exceeded its timeshare – it does not run
- Task with the earliest virtual deadline is selected to run next
- Virtual deadlines enable latency-sensitive tasks with shorter-time slices to be prioritized more than CFS which helps improve responsiveness
- More info: https://docs.kernel.org/scheduler/sched-eevdf.html

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QUESTIONS

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