TCSS 422: OPERATING SYSTEMS

Multi-level Feedback Queue II, Proportional Share Schedulers, Linux Completely Fair Scheduler

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

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TEXT BOOK COUPON

- 15% off textbook code: **HAPPYPLANET15** (*through Friday Apr 25*)
- 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

- <u>Office Hours plan for Spring (by Zoom):</u>
- Monday 11:30am - 12:30p GTA Xinghan
- Tuesday 11:30am - 12:30p GTA Xinghan
- Wednesday ~~11:00am - 12:00p~~ Instructor Wes
  - THIS WEEK: 5:30 to 6:30pm CP 229 & Zoom Instructor Wes
- Friday 12:00pm - 1:00p Instructor Wes or GTA Xinghan

- Office hours this Friday April 18th
  - Wes

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

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BONUS SESSION – CPU SCHEDULING PROBLEMS

- To help prepare for quiz 1 and the midterm

- Wednesday April 23, 4 to 5pm
- MLG 311 and live-streamed on Zoom
- Recording will be posted

- Sample problems will be solved
- Sample problems are posted online:
- https://faculty.washington.edu/wlloyd/courses/tcss422/scheduler_examples_s2025.pdf

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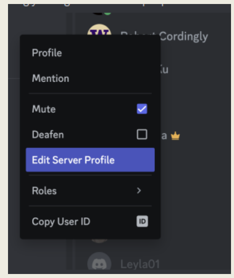
TCSS 422 DISCORD SERVER

- Please join the TCSS 422 A – Spring 2025 Discord Server
- https://discord.gg/H7PPZ5ArFW
- Under Edit Server Profile:
  Please update your 'Server Nickname' to your real name or UW NET ID
  THANK YOU



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OBJECTIVES – 4/22

- Questions from 4/17
- Assignment 0 - Due Fri Apr 26
- C Tutorial - Pointers, Strings, Exec in C - Due Fri Apr 30
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  - Critical section

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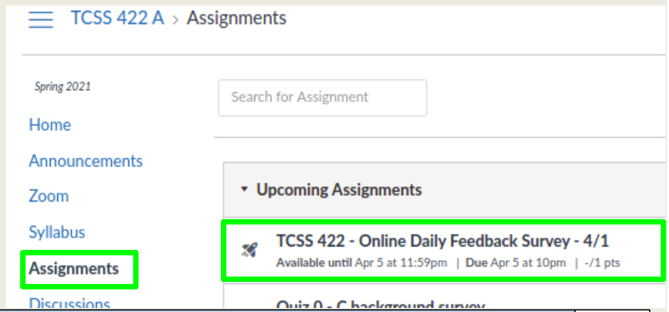
ONLINE DAILY FEEDBACK SURVEY

- 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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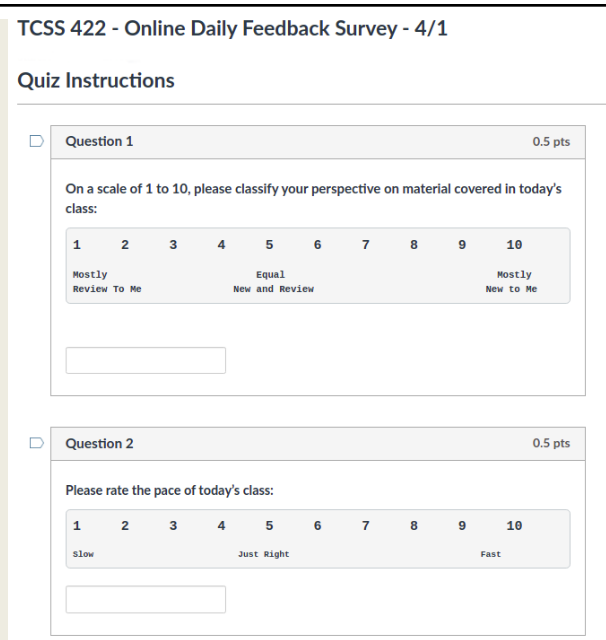

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (44 of 63 respondents – 69.8%) :
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.32 (↓ - previous 6.88)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 4.98 (↓ - previous 5.05)**

FEEDBACK FROM 4/17

- ***Round-robin schedulers are excellent for providing low job response time - but they sacrifice job turnaround time.***

- ***For process scheduling, why is it generally better for schedulers to satisfy both response time and turnaround time?***
  - This is how the Multi-level Feedback Queue (MLFQ) improves on the round-robin scheduler

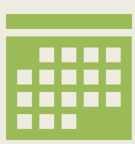
- ***IDEA: Could schedulers distribute tasks to dedicated processors with specialized roles for handling interactive jobs and batch (long-running & high-CPU-load) jobs?***

FEEDBACK - 2

- ***How is the MLFQ itself scheduled within the OS ?***
  Is the scheduler assigned a dedicated time slice to prevent a higher priority job from keeping it from running ?
- ***How can we be sure that priority boosts and job priority adjustments can continue to occur ?***

- Remember that preemptive multitasking operating systems feature a timer interrupt. This interrupt is setup at boot time. The timer fires every ~2 to 10ms to perform a non-voluntary context switch. Also when the user performs I/O, this creates voluntary context switches.
- These context switches allow the system to take over, and the OS kernel can run the MLFQ scheduler to manage jobs running on the system
  - MLFQ will priority boost, adjust job priority among queues, etc.

REVIEW



In the context of process scheduling, what is a "batch job" ?

What is an "interactive job" ?

FEEDBACK - 3

- ***Which of these scheduler's do today's operating systems use?***
- Chapter 9 introduces the **Linux Completely Fair Scheduler (CFS)**
- CFS was used until version 6.5 of the Linux kernel
- Starting with Linux kernel 6.6+ (Oct 29 2023), CFS was replaced with the **Earliest Eligible Virtual Deadline First (EEVDF)** scheduler
- Ubuntu 24.04 LTS launched with the 6.8 Linux Kernel, and is now using 6.11 this quarter which is EEVDF
- We will not test on the EEVDF scheduler since it is not in the textbook
  - I created 1 slide on EEVDF at the end of Chapter 9

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FEEDBACK - 4

- ***What is going to be on the quiz ?***
- ***What is going to be on the quiz ??***
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  - Introduction
  - Race condition
  - Critical section

ASSIGNMENT 0 - DUE FRI APR 26

- Due Friday April 26 AOE (Apr 27 4:59am)
- Grace period: submission ok until Tue Apr 29 @ 4:59 **AM**
- Late submissions thru Tuesday Thur May 1 @ 4:59am

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QUIZ 1

- Active reading on Chapter 9 – Proportional Share Schedulers
- Posted in Canvas
- Due Thursday May 1st AOE (Fri May 2 4:59 am)
- **Link:**
- https://faculty.washington.edu/wlloyd/courses/tcss422/quiz/TCSS422_s2025_quiz_1.pdf

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QUIZ 2

- Canvas Quiz – Practice CPU Scheduling Problems
- Posted in Canvas
- Unlimited attempts
- Due Tuesday May 6th AOE (May 7th at 4:59am)
- **Link:**
- https://canvas.uw.edu/courses/1809484/assignments/10329061

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COMING SOON...

- Assignment #1
  - To be posted soon

- Quiz 1
  - Thursday April 24th
  - In Class – BHS 106
  - 4:40 – 5:40 pm
  - Open notes, open books, no digital devices

- Midterm Exam
  - Thursday May 8th
  - In Class – BHS 106
  - 3:40 – 5:40 pm
  - 3 pages of notes double-sides, no digital devices

CATCH UP FROM LECTURE 6

- Switch to Lecture 6 Slides
- Slides L6.43 to L6.50 (MLFQ priority boost, MLFQ summary)

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Jackson deploys a 3-level MLFQ scheduler. The time slice is 1 for high priority jobs, 2 for medium priority, and 4 for low priority. This MLFQ scheduler performs a Priority Boost every 6 timer units. When the priority boost fires, the current job is preempted, and the next scheduled job is run in round-robin order.

***SANITY CHECK*: Consider the timing graph x-axis should not exceed the combined job length of all jobs.**

Job	Arrival Time	Job Length
A	T=0	4
B	T=0	16
C	T=0	8

(11 points) Show a scheduling graph for the MLFQ scheduler for the jobs above.
Draw vertical lines for key events and be sure to label the X-axis times as in the example.
Please draw clearly. An unreadable graph will loose points.

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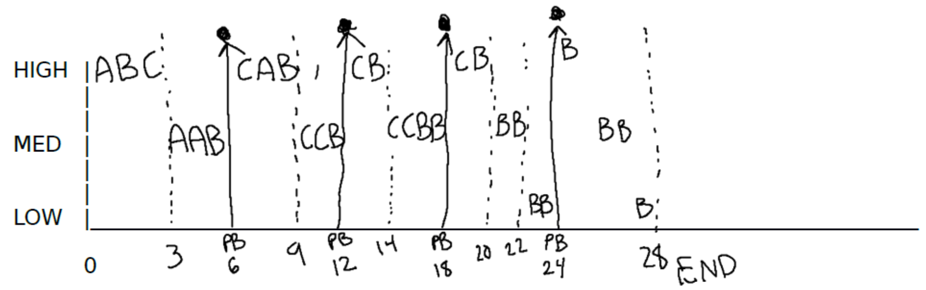

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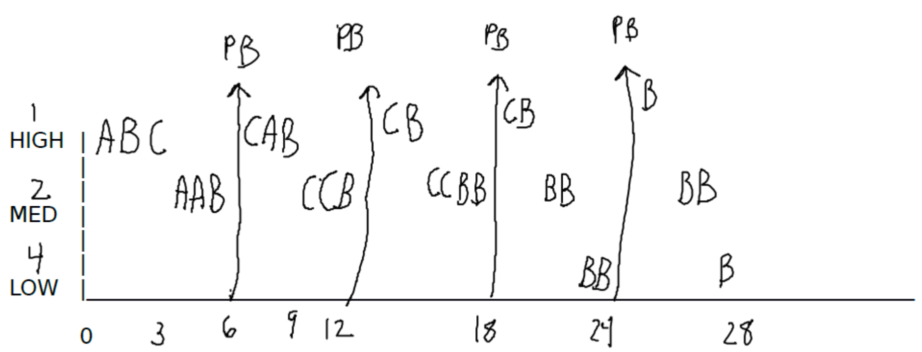
Job	Arrival Time	Job Length
A	T=0	
B	T=0	
C	T=0	

time slice is JOB time Before c/s

(11 points) Show a scheduling graph for the MLFQ scheduler for the jobs above.
Draw vertical lines for key events and be sure to label the X-axis times as in the example.
Please draw clearly. An unreadable graph will loose points.



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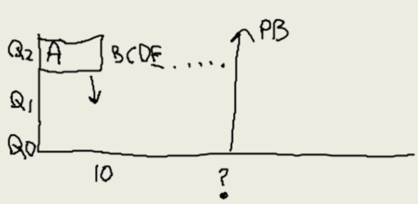
EXAMPLE

- Question:
- Given a system with a quantum length of 10 ms ***for all jobs*** in its highest queue, how often would you have to boost job A (the first job to arrive and run) back to the highest priority level to guarantee that job A, a long-running (and potentially starving) job gets at least 5% of the CPU assuming that on priority boost job execution resets to the front of the queue?

EXAMPLE

- Question:
- Given a system with a total quantum length of 10 ms ***for all jobs*** to run before priority is lowered in the highest queue, how often would you have to boost jobs back to the highest priority level to guarantee that a single long-running (and potentially starving) job gets at least 5% of the CPU?



$$.05\ PB = 10$$

$$PB = \frac{10}{.05} = 200\ ms$$

EXAMPLE

- Question:
- Given a system with a quantum length of 10 ms ***for all jobs*** in its highest queue, how often would you have to boost jobs back to the highest priority level to guarantee that a single long-running (and potentially starving) job gets at least 5% of the CPU?

- Some combination of n short jobs runs for a total of 10 ms per cycle without relinquishing the CPU
  - E.g. 2 jobs = 5 ms ea; 3 jobs = 3.33 ms ea, 10 jobs = 1 ms ea
  - n jobs always uses full time quantum in highest queue (10 ms)
  - Batch jobs starts, runs for full quantum of 10ms, pushed to lower queue
  - All other jobs run and context switch totaling the quantum per cycle
  - If 10ms is 5% of the CPU, when must the priority boost be ???
  - **ANSWER** → ***Priority boost should occur every 200ms***

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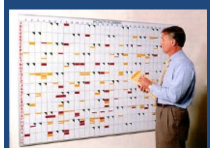
CHAPTER 9 - PROPORTIONAL SHARE SCHEDULER



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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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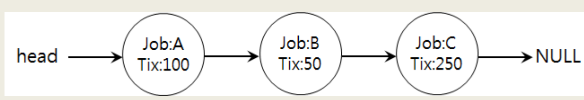
LOTTERY SCHEDULER

- 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

LOTTERY SCHEDULER IMPLEMENTATION




```
// counter: used to track if we've found the winner yet
int counter = 0;

// winner: use some call to a random number generator to
// get a value, between 0 and the total # of tickets
int winner = getrandom(0, totaltickets);

// current: use this to walk through the list of jobs
node_t *current = head;

// loop until the sum of ticket values is > the winner
while (current) {
        counter = counter + current->tickets;
        if (counter > winner)
                break; // found the winner
        current = current->next;
}
// 'current' is the winner: schedule it...
```

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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)

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.

LOTTERY SCHEDULING

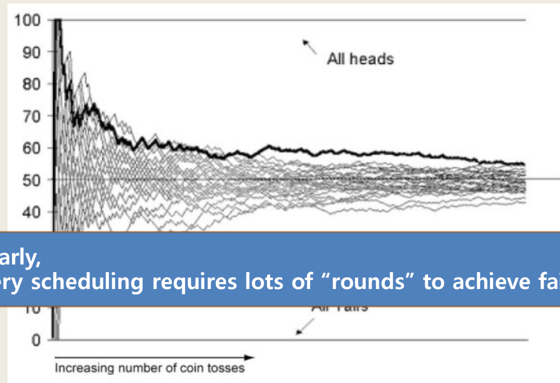
- Scheduler picks a **winning** ticket
  - Load the job with the winning ticket and run it
- Example:
  - Given 100 tickets in the pool
    - Job A has 75 tickets: 0 - 74
    - Job B has 25 tickets: 75 – 99

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?

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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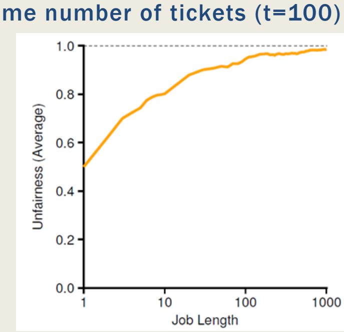
LOTTERY FAIRNESS

- 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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STRIDE SCHEDULER

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

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…

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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

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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

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	…

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 …

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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	…

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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

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WE WILL RETURN AT 5:02PM

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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 !

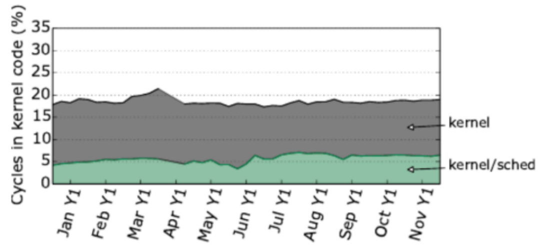

Figure 5: Kernel time, especially time spent in the scheduler, is a significant fraction of WSC cycles.

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 (class) receives exactly $1/n^{th}$ of the CPU time
- Each scheduling class has a runqueue
  - Groups processes of the same class
  - In the class, scheduler 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):
- **Normal classes**: SCHED_OTHER (TS), SCHED_IDLE, 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 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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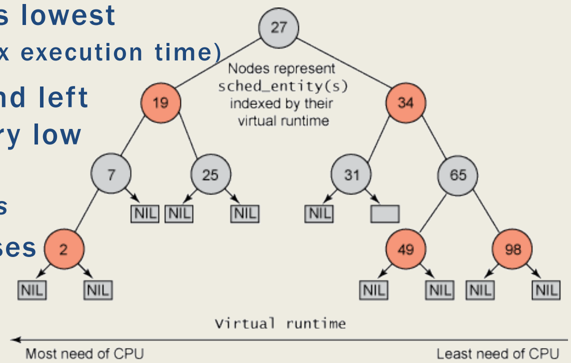
COMPLETELY FAIR SCHEDULER - 5

- 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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CFS: JOB PRIORITY

- Time slice: 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 on a given runqueue 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
  - **GOAL:** Perfect scheduler → achieve equal **vruntime** for all processes of same priority
- 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 assigns a virtual runtime to each task, creating a "lag" value that is used to determine whether a task has received its fair share of CPU time
  - A task with a positive lag is owed CPU time
  - A task with negative lag has exceeded its timeshare
- EEVDF calculates a virtual deadline (VD) for each task with lag greater or equal to zero
- 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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OBJECTIVES – 4/22

- Questions from 4/17
- Assignment 0 - Due Fri Apr 26
- C Tutorial - Pointers, Strings, Exec in C - Due Fri Apr 30
- Quiz 1 and Quiz 2
- Chapter 8: Multi-level Feedback Queue
  - Gaming the Scheduler
  - Examples
- Chapter 9: Proportional Share Schedulers
  - Lottery scheduler
  - Ticket mechanisms
  - Stride scheduler
  - Linux Completely Fair Scheduler
- Chapter 26: Concurrency: An Introduction
  - **Introduction**
  - Race condition
  - Critical section

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CHAPTER 26 - CONCURRENCY: AN INTRODUCTION

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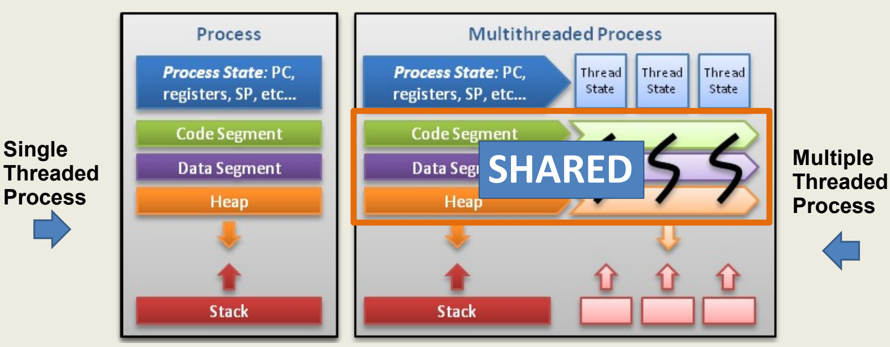
THREADS



©Alfred Park, http://randu.org/tutorials/threads

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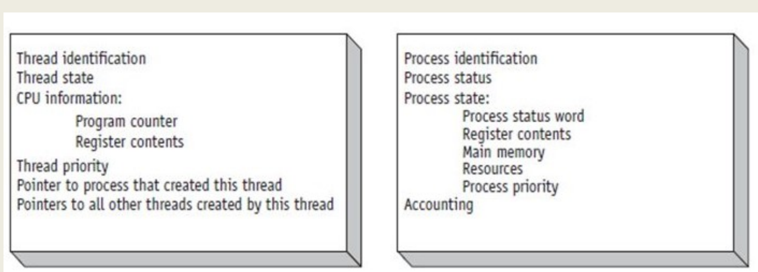
THREADS - 2

- Enables a single process (program) to have multiple "workers"
  - This is parallel programming...
- Supports independent path(s) of execution within a program *with shared memory* ...
- Each thread has its own Thread Control Block (TCB)
  - PC, registers, SP, and stack
- Threads share code segment, memory, and heap are shared
- ***What is an embarrassingly parallel program?***

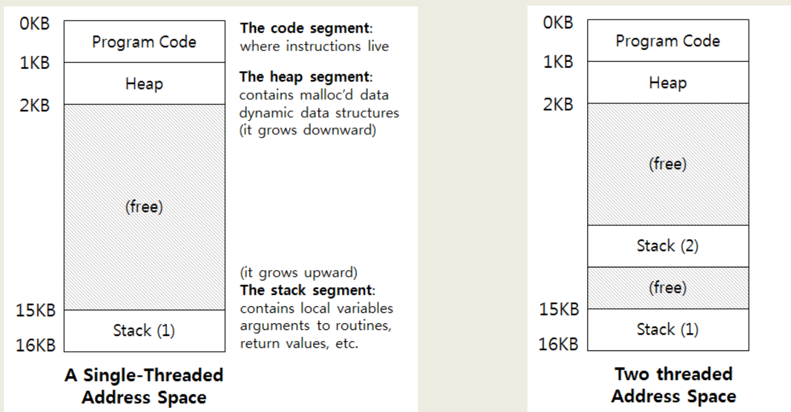
PROCESS AND THREAD METADATA

- Thread Control Block vs. Process Control Block



SHARED ADDRESS SPACE

- Every thread has it's own stack / PC



THREAD CREATION EXAMPLE

```
#include <stdio.h>
#include <assert.h>
#include <pthread.h>

void *mythread(void *arg) {
    printf("%s\n", (char *) arg);
    return NULL;
}

int
main(int argc, char *argv[]) {
    pthread_t p1, p2;
    int rc;
    printf("main: begin\n");
    rc = pthread_create(&p1, NULL, mythread, "A"); assert(rc == 0);
    rc = pthread_create(&p2, NULL, mythread, "B"); assert(rc == 0);
    // join waits for the threads to finish
    rc = pthread_join(p1, NULL); assert(rc == 0);
    rc = pthread_join(p2, NULL); assert(rc == 0);
    printf("main: end\n");
    return 0;
}
```

POSSIBLE ORDERINGS OF EVENTS

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
Creates Thread 2		
Waits for T1		
	Runs	
	Prints 'A'	
	Returns	
Waits for T2		
		Runs
		Prints 'B'
		Returns
Prints 'main: end'		

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POSSIBLE ORDERINGS OF EVENTS - 2

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
	Runs	
	Prints 'A'	
	Returns	
Creates Thread 2		
		Runs
		Prints 'B'
		Returns
Waits for T1	*Returns immediately*	
Waits for T2		*Returns immediately*
Prints 'main: end'		

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POSSIBLE ORDERINGS OF EVENTS - 3

int main()	Thread 1	Thread 2
Starts running		
Prints 'main: begin'		
Creates Thread 1		
Creates Thread 2		
Waits for T		
	Runs	
	Prints 'A'	
	Returns	
Waits for T2		*Immediately returns*
Prints 'main: end'		

What if execution order of events in the program matters?

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COUNTER EXAMPLE

- Counter example
- A + B : ordering
- Counter: incrementing global variable by two threads
- ***Is the counter example embarrassingly parallel?***
- ***What does the parallel counter program require?***

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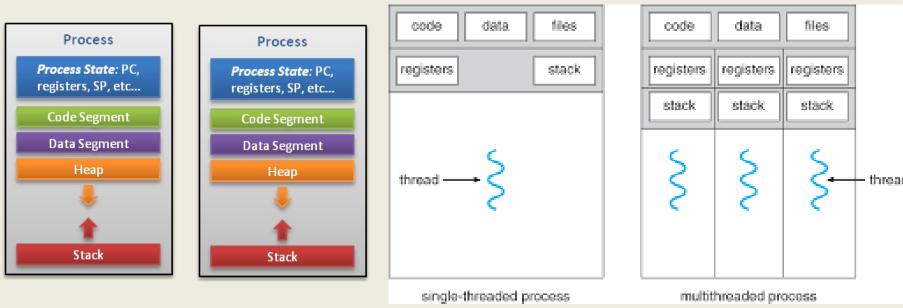
PROCESSES VS. THREADS

- What's the difference between forks and threads?
  - Forks: duplicate a process
  - Think of ***CLONING*** **-** There will be two identical processes at the end
  - Threads: no duplication of code/heap, lightweight execution threads



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  - **Race condition**
  - Critical section

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RACE CONDITION

- What is happening with our counter?
  - When counter=50, consider code: counter = counter + 1
  - If synchronized, counter will = 52

OS	Thread1	Thread2	PC (after instruction)	%eax (after instruction)	counter (after instruction)
	before critical section		100	0	50
	mov 0x8049a1c, %eax		105	50	50
	add $0x1, %eax		108	51	50
interrupt					
save T1's state					
restore T2's state			100	0	50
		mov 0x8049a1c, %eax	105	50	50
		add $0x1, %eax	108	51	50
		mov %eax, 0x8049a1c	113	51	51
interrupt					
save T2's state					
restore T1's state			108	51	50
	mov %eax, 0x8049a1c		113	51	**51**

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  - **Critical section**

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CRITICAL SECTION

- Code that accesses a shared variable must not be ***concurrently*** executed by more than one thread
- Multiple *active* threads inside a ***critical section*** produce a ***race condition***.
- ***Atomic execution*** (*all code executed as a unit*) must be ensured in ***critical*** sections
  - These sections must be ***mutually exclusive***

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LOCKS

- To demonstrate how critical section(s) can be executed "atomically-*as a unit*" Chapter 27 & beyond introduce locks

```
lock_t mutex;
. . .
lock(&mutex);
balance = balance + 1;
unlock(&mutex);
```

Critical section

- Counter example revisited

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QUESTIONS

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