History & Scheduler (Start)

Computer Operating Systems, Spring 2025

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- How are you doing? What do you know about ENIAC?

Administrivia

- Penn-shell is out (this shouldn't be news)!
  - ***Full thing is due (Mon, June 23) (Start of next week!)***
  - ***Done in partners***
    - Everything was covered already that you would need…
- Midterm is Wednesday next week
  - Old exams and exam policies are posted on the course website
  - Some midterm review in Lecture Tuesday Next Week

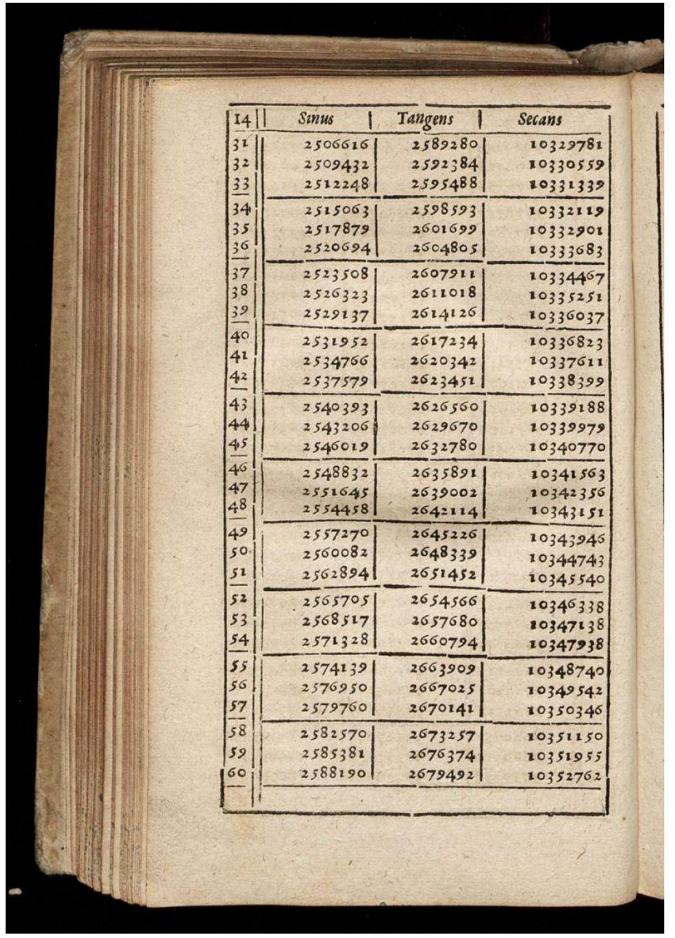
Lecture Outline

- **Women as the First Operating System**
- Scheduling History
- Scheduling Overview
- Types of Scheduling Algorithms

Mathematical Tables

- Before non-human calculators, you'd look up the result of a computation in a table. (Logarithm Tables, Square Root Tables ….)

- These were calculated by "Human-Computers"
  - Difficult to make tables, but made calculations faster once you had them



14	Sinus	Tangens	Secans
31	2506616	2589280	10329781
32	2509432	2592384	10330559
33	2512248	2595488	10331339
34	2515063	2598593	10332119
35	2517879	2601699	10332901
36	2520694	2604805	10333683
37	2523508	2607911	10334467
38	2526323	2611018	10335251
39	2529137	2614126	10336037
40	2531952	2617234	10336823
41	2534766	2620342	10337611
42	2537579	2623451	10338399
43	2540393	2626560	10339188
44	2543206	2629670	10339979
45	2546019	2632780	10340770
46	2548832	2635891	10341563
47	2551645	2639002	10342356
48	2554458	2642114	10343151
49	2557270	2645226	10343946
50	2560082	2648339	10344743
51	2562894	2651452	10345540
52	2565705	2654566	10346338
53	2568517	2657680	10347138
54	2571328	2660794	10347938
55	2574139	2663909	10348740
56	2576950	2667025	10349542
57	2579760	2670141	10350346
58	2582570	2673257	10351150
59	2585381	2676374	10351955
60	2588190	2679492	10352762

Human Computers

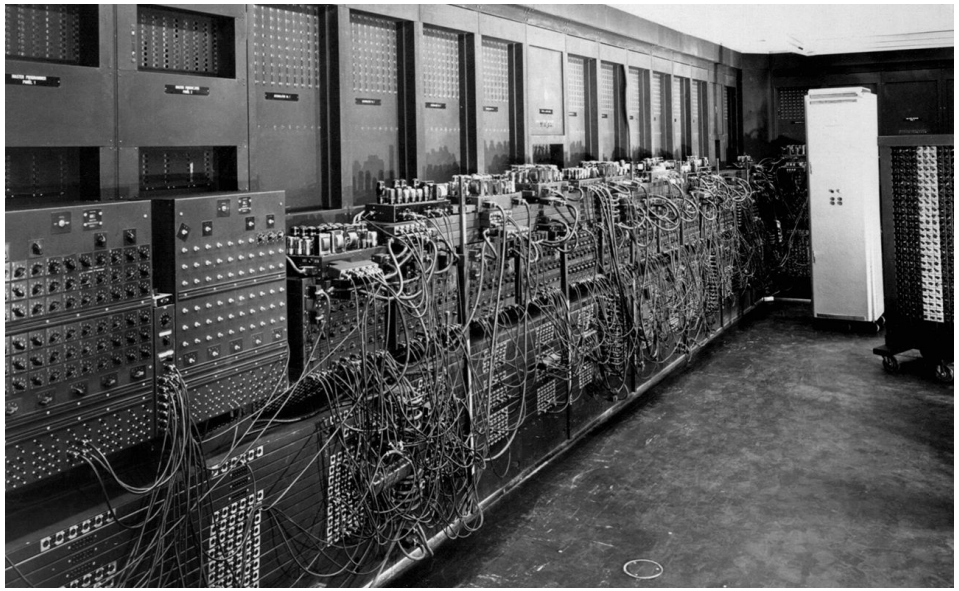
Human computers were employed for math computation, not yet "computer programming" as we know it today

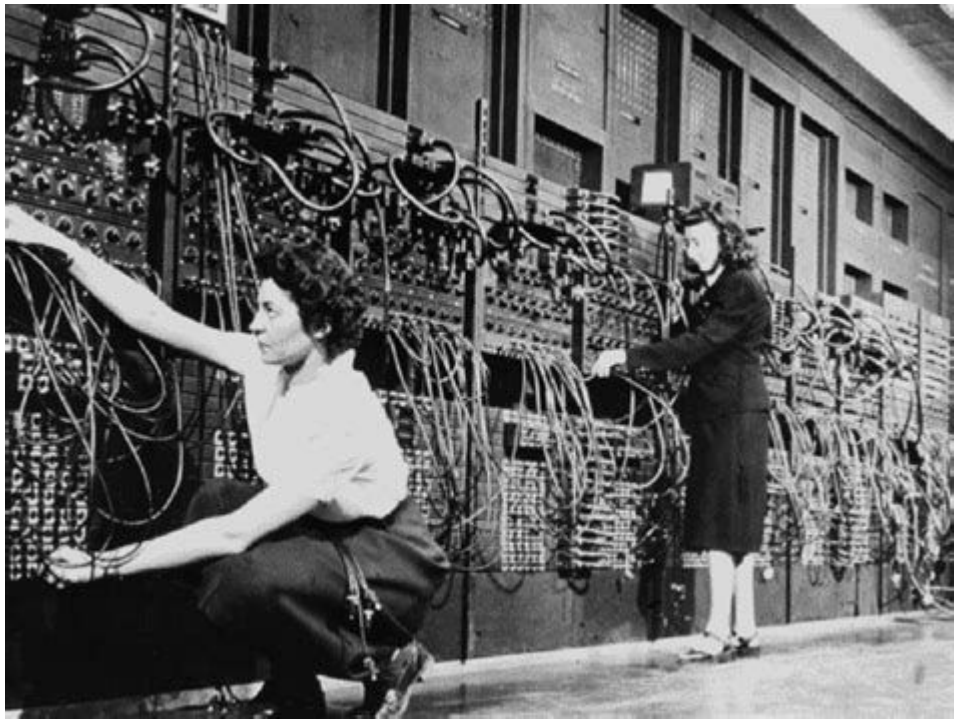
Gendered as a "woman's job"

- "Requires patience, persistence, and a capacity for detail… that many girls have"
- Likened to secretary work: both manual and also meant to assist (male) professionals
- Still requires highly technical knowledge

ENIAC - 1945

- Electronic Numerical Integrator and Computer
- First programmable, electronic, general-purpose, digital computer
- Developed in Moore Building for the military: artillery trajectory tables
- Keep your eyes out for Feb 15, 2026 (80th yr anni)





ENIAC - 40 units

Arithmetic

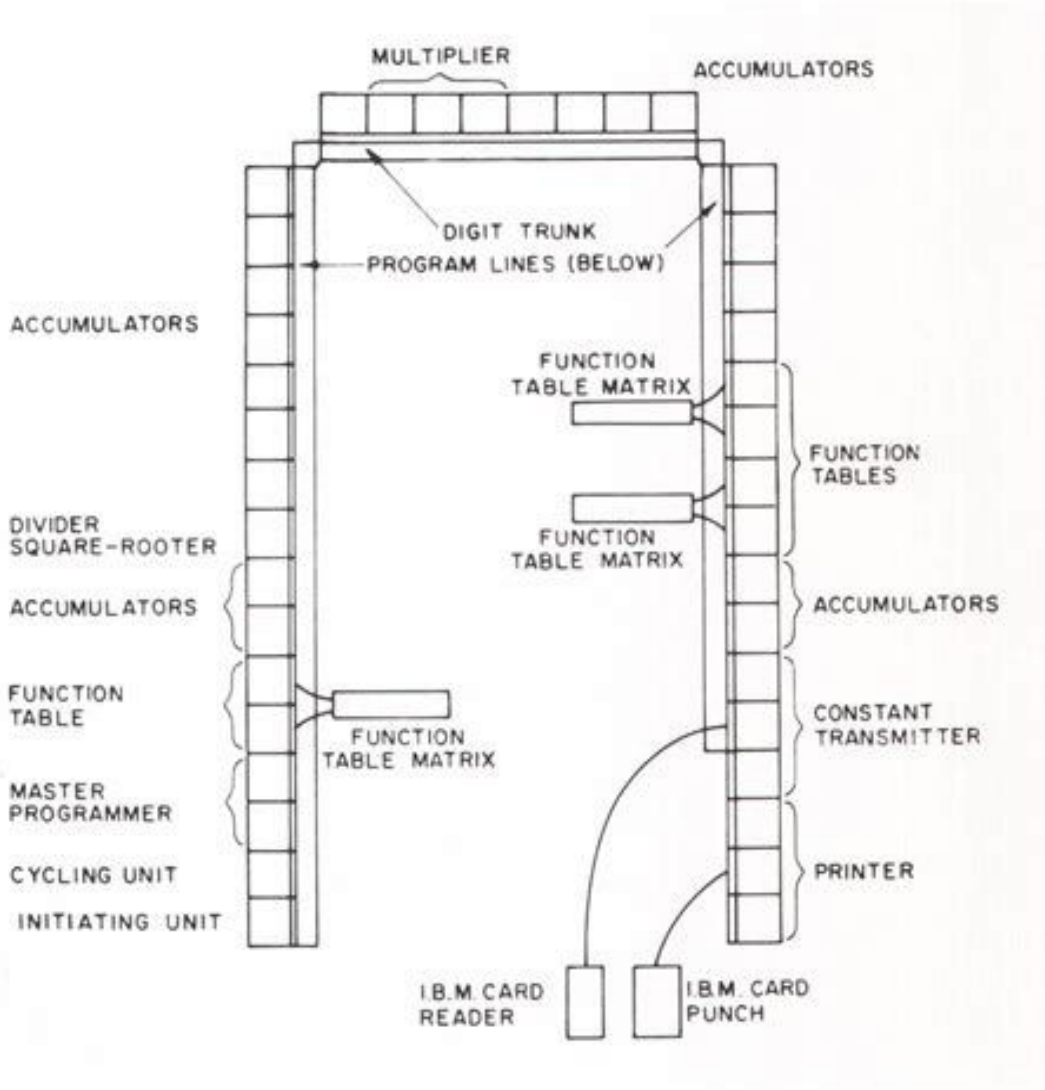
- 20 accumulators* (registers that can add and subtract within itself)
- 1 fast multiplier
- 1 divider and square rooter

Memory & I/O

- 3 function tables*
- Constant transmitter*
- Punch card reader*
- Punch card writer*

Governing (Control Flow)

- Initiating unit
- Cycling unit
- Master programmer*



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Governing (Control Flow)

- Initiating unit
- Cycling unit
- Master programmer*

For math calculations, how much faster?

- 500 multiplications and 5,000 additions every second

- 30 hours of hand calculations became 20 seconds of computer runtime
  - 3 days of setup, not including debug time

Who got to touch the computer?

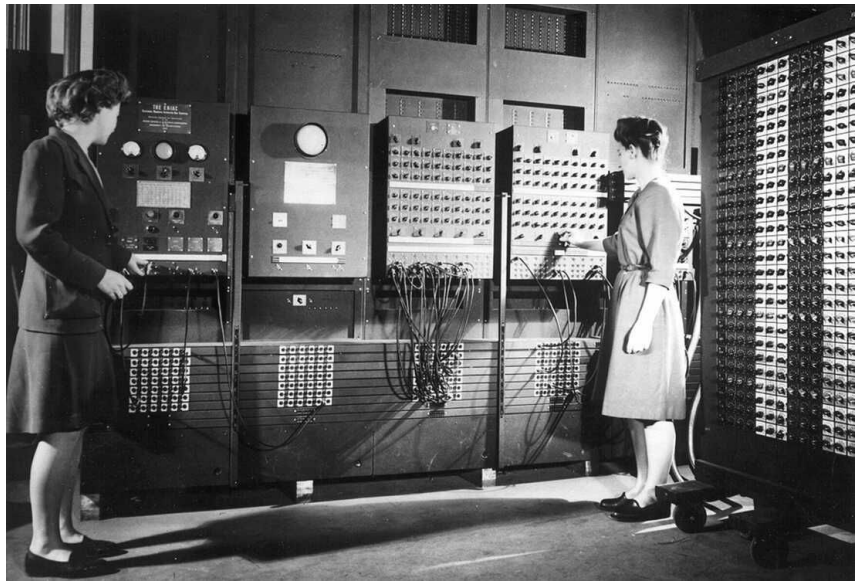
- The engineers who built the computer
- Secretaries who generated punch card inputs
- Computer programmers and operators
- University researchers
- Students
- Anyone who walked in when no-one was looking?

The ENIAC 6

"The Eniac's Operating System"

First Programmers of ENIAC:

- Betty Holberton
- Jean Bartik
- Ruth Teitelbaum
- Kathleen Antonelli
- Marlyn Meltzer
- Frances Spence



The Necessity of Programmers

- Operating the ENIAC is complex!!
  - For a program that would take 2 lines of pseudocode, there is a 10-page tutorial with 10 figures and 3 tables
- 40 separate units that can run in parallel
- Machines can only perform math (and a little control flow)
  - A lot of overhead fell on the humans operating the computer

The ENIAC 6: providing the overhead

Programmer / Compiler

- Translate the mathematical problem into smaller programs ENIAC can run

loader

- Set up the 40 panels of ENIAC to run the program

OS

- Operate the computer:
  - Start the computer, ensure everything is running well
  - Manage "I/O" to handle intermediate values if they are too large to handle
  - Manage where values are stored in hardware and ensure data is being written / read following correct timing requirements

operator

- Debug ☺
  - If the program was wrong
  - Inevitably: when a piece of hardware broke

Note: not much really in terms of scheduling (yet). ENIAC only did one program at a time.

The ENIAC 6

"The ENIAC was a son-of-a-bitch to program" – Jean Jennings Bartik

- Simultaneously navigating an all-male landscape in Penn's Engineering facilities
  - Received sub-professional occupation classification -> less pay
  - Unable to be authored in any papers or manuals
  - Unprivileged access to the ENIAC - learned programming in a separate room
  - Served as "hostesses" during ENIAC's public release

Lecture Outline

- Women as the First Operating System
- **Scheduling History**
- Scheduling Overview
- Types of Scheduling Algorithms

Computer Access

- Revisiting the question of: who do we let access the computer…?
- This affects how we will be able to schedule multiple programs to run within a day

Idea #1: Everyone gets access!

What issues will we run into?

Idea #1: Everyone gets access!

What issues will we run into?

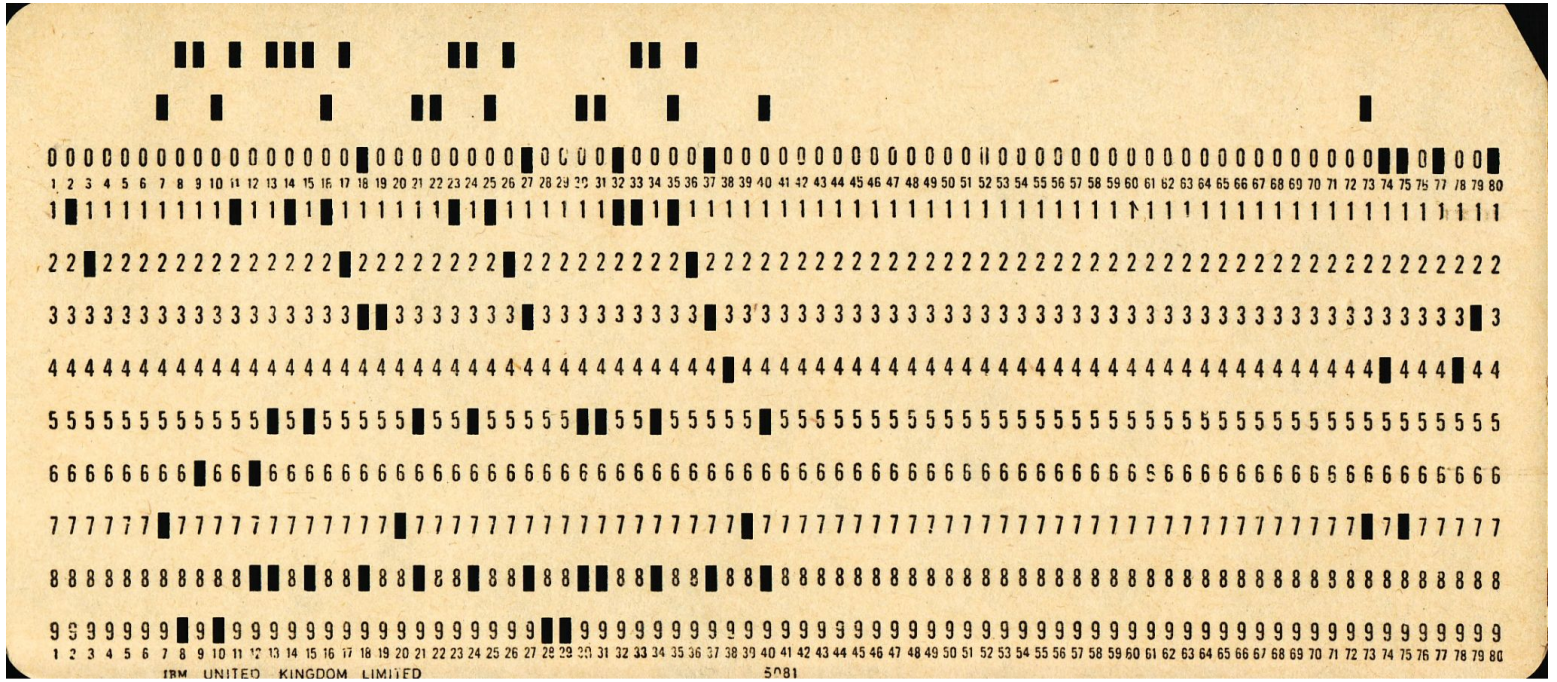
- "Rush hour" - what if people all try to get their program run at the same time?
- Large gaps of time when computer runs without a program - wasted cycles
- Does everyone in the building know how to use the computer properly?
- What happens if the computer fails / halts?

Idea #2: Reservations

- Block out a time when only you are allowed to use the computer - shared calendar
- Fixes the problem of multiple people trying to access the computer at the same time
- Need multiple operators working round-the-clock in shifts in case of failure
- What is wrong with this idea?

Idea #3: Dropoff

- People who want a job done submit their stack(s) of punch cards to a “front desk”
- Operators gather the stacks together and inserts programs in chronological order*



Batch Processing

- 1950's
- First instance of computer handling the scheduling
- Operator gets stacks of punch cards from multiple jobs, groups into a mega-stack and then shoves into computer
- Computer runs through the jobs sequentially, and will provide outputs once finished with *all jobs* in the batch
- Required its own language: Job Control Language (JCL)

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- Comparing batch processing to the reservation system:
  - Which has better **latency**? (average speed of 1 job)
  - Which has better **throughput**? (# jobs per time)

Efficiency towards Automation

- Why do we care about latency and throughput?
- Improvements in computing is highly motivated by automation
- How to make things faster/easier
  - Making the calculations itself faster
  - But also automating the operator tasks
  - “being fast” is not the only type of efficiency we’re concerned about
- Is efficiency the end-all be-all? This is for after your midterm :)

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OS as the Scheduler

- The scheduler is code that is part of the kernel (OS)

- The scheduler runs when a task:
  - Starts ("arrives to be scheduled"),
  - Finishes
  - Blocks (e.g., waiting on something, usually some form of I/O)
  - Has run for a certain amount of time

- It is responsible for scheduling tasks
  - Choosing which one to run
  - Deciding how long to run it

Scheduler Terminology

- The scheduler has a scheduling algorithm to decide what runs next.

- Algorithms are designed to consider many factors:
  - Fairness: Every program gets to run
  - Liveness: That “something” will eventually happen
  - Throughput: amount of work completed over an interval of time
  - Wait time: Average time a “task” is “alive” but not running
  - Turnaround time: time between task being ready and completing
  - Response time: time it takes between task being ready and when it can take user input
  - Etc…

Goals

- The scheduler will have various things to prioritize
- Some examples:
- Minimizing wait time
  - Get tasks started as soon as possible
- Minimizing latency
  - Quick response times and task completions are preferred
- Maximizing throughput
  - Do as much work as possible per unit of time
- Maximizing fairness
  - Make sure every task can execute fairly

- These goals depend on the system and can conflict

Scheduling: Other Considerations

- It takes time to context switch between tasks
  - Could get more work done if task switching is minimized
- Scheduling takes resources
  - It takes time to decide which task to run next
  - It takes space to hold the required data structures
- Different tasks have different priorities
  - Higher priority tasks should finish first

Lecture Outline

- Women as the First Operating System
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- **Types of Scheduling Algorithms**

Types of Scheduling Algorithms

- **Non-Preemptive:** if a task is running, it continues to run until it completes or until it gives up the CPU
  - First Come First Serve (FCFS)
  - Shortest Job First (SJF)

- **Preemptive:** the task may be interrupted after a given time and/or if another task becomes ready
  - Round Robin
  - Priority Round Robin
  - …

First Come First Serve (FCFS)

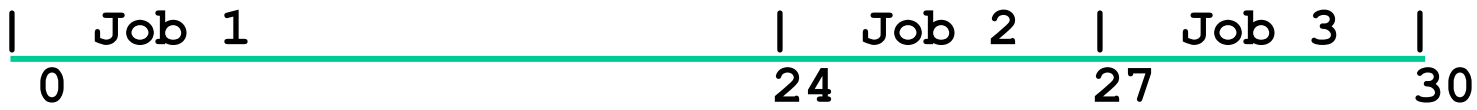
- Idea: Whenever a task is ready, schedule it to run until it is finished (or blocks).
- Maintain a queue of ready tasks
  - Tasks go to the back of the queue when it arrives or becomes unblocked
  - The task at the front of the queue is the next to run

Example of FCFS

1 CPU
Job 2 arrives slightly after job 1.
Job 3 arrives slightly after job 2

- Example workload with three "jobs" (tasks):
  Job 1: 24 time units; Job 2: 3 units; Job 3: 3 units

- FCFS schedule:



- Total waiting time: 0 + 24 + 27 = 51
- Average waiting time: 51/3 = 17
- Total turnaround time: 24 + 27 + 30 = 81
- Average turnaround time: 81/3 = 27

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- What are the advantages/disadvantages/concerns with **First Come First Serve**

- Things a scheduler should prioritize:
  - Minimizing wait time
  - Minimizing Latency
  - Maximizing fairness
  - Maximizing throughput
  - Task priority
  - Cost to schedule things
  - Cost to context Switch

- Imagine we have 1 core, and tasks of various (finite) lengths…

FCFS Analysis

- Advantages:
  - Simple, low overhead
  - Hard to screw up the implementation
  - Each task will DEFINITELY get to run eventually.

- Disadvantages
  - Doesn’t work well for interactive systems
  - Throughput can be low due to long tasks running uninterrupted
  - Large fluctuations in average turn around time
  - Priority not taken into considerations

Shortest Job First (SJF)

- Idea: variation on FCFS, but have the tasks with the smallest CPU-time requirement run first
  - Arriving jobs are instead put into the queue depending on their run time, shorter jobs being towards the front
  - Scheduler selects the shortest job (1st in queue) and runs till completion

Example of SJF

1 CPU
Job 2 arrives slightly after job 1.
Job 3 arrives slightly after job 2

- Same example workload with three "jobs":
  Job 1: 24 time units; Job 2: 3 units; Job 3: 3 units

- SJF schedule:

- Total waiting time: 6 + 0 + 3 = 9
- Average waiting time: 3
- Total turnaround time: 30 + 3 + 6 = 39
- Average turnaround time: 39/3 = 13

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- What are the advantages/disadvantages/concerns with **Shortest Job First**

- Things a scheduler should prioritize:
  - Minimizing wait time
  - Minimizing Latency
  - Maximizing fairness
  - Maximizing throughput
  - Task priority
  - Cost to schedule things
  - Cost to context Switch

- Imagine we have 1 core, and tasks of various (finite) lengths …

SJF Analysis

- Advantages:
  - Still relatively simple, low overhead
  - Provably minimal average turnaround time

- Disadvantages
  - Starvation possible
    - If quick jobs keep arriving, long jobs will keep being pushed back and won't execute
  - How do you know how long it takes for something to run?
    - You CAN'T. You can use a history of past behavior to make a guess.
  - Priority not taken into consideration

Types of Scheduling Algorithms

- **Non-Preemptive:** if a task is running, it continues to run until it completes or until it gives up the CPU
  - First Come First Serve (FCFS)
  - Shortest Job First (SJF)

- **Preemptive:** the task may be interrupted after a given time and/or if another task becomes ready
  - Round Robin
  - Priority Round Robin
  - …

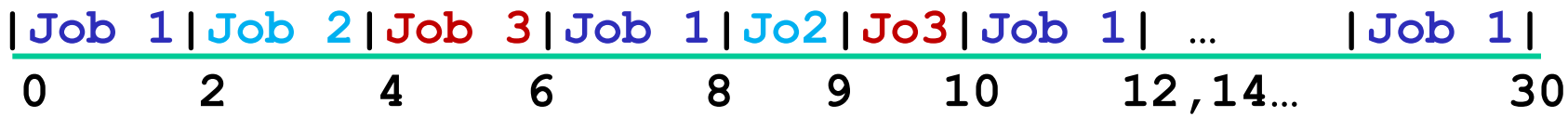
Round Robin

- Sort of a preemptive version of FCFS
  - Whenever a task is ready, add it to the end of the queue.
  - Run whatever task is at the front of the queue

- BUT only led it run for a fixed amount of time (quantum).
  - If it finishes before the time is up, schedule another task to run
  - If time is up, send the running task back to the end of the queue.

Example of Round Robin

- Same example workload:
  Job 1: 24 units, Job 2: 3 units, Job 3: 3 units
- RR schedule with time quantum = 2:



- Total waiting time: (0 + 4 + 2) + (2 + 4) + (4 + 3) = 19
  - Counting time spent waiting between each “turn” a job has with the CPU
- Average waiting time: 19/3 (~6.33)
- Total turnaround time: 30 + 9 + 10 = 49
- Average turnaround time: 49/3 (~16.33)

Poll Everywhere

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- What are the advantages/disadvantages/concerns with **Round Robin**

- Things a scheduler should prioritize:
  - Minimizing wait time
  - Minimizing Latency
  - Maximizing fairness
  - Maximizing throughput
  - Task priority
  - Cost to schedule things
  - Cost to context Switch

- Imagine we have 1 core, and tasks of various lengths…

Round Robin Analysis

- Advantages:
  - Still relatively simple
  - Can works for interactive systems

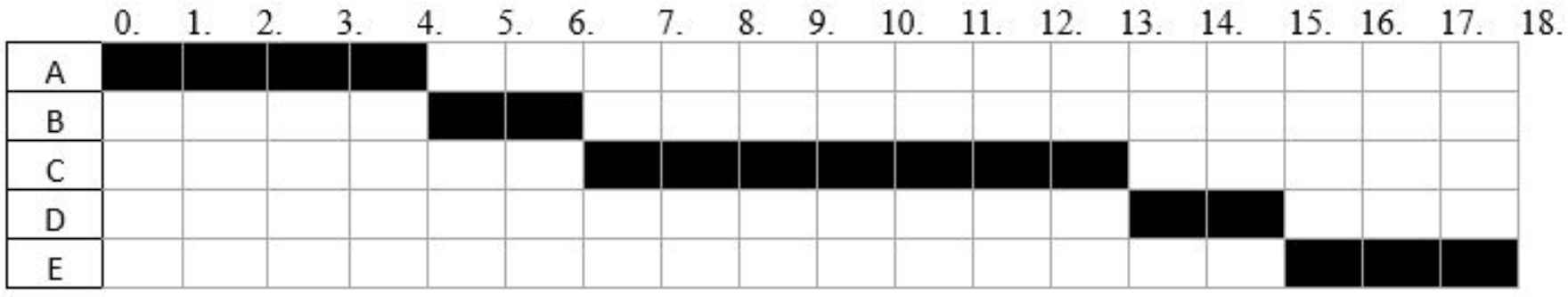
- Disadvantages
  - If quantum is too small, can spend a lot of time context switching
  - If quantum is too large, approaches FCFS
  - Still assumes all processes have the same priority.

- Rule of thumb:
  - Choose a unit of time so that most jobs (80-90%) finish in one usage of CPU time

Round Robin Practice!

- Assume that we had the following set of processes that ran on a single CPU following the First Come First Serve (FCFS) scheduling policy.
- If we expressed this with a drawing, where a black square represents that the process is executing, we would get:

Process	Arrival Time	Job Length	Finish Time (FCFS)
A	0	4	4
B	1	2	6
C	2	7	13
D	3	2	15
E	4	3	18



Round Robin Practice!

- Instead, let's switch our algorithm to round-robin with a time quantum of 3 time units.

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A	0	4	4
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- You can assume:
  - Context switching and running the Scheduler are instantaneous.
  - If a process arrives at the same time as the running process's time slice finishes, the one that just arrived goes into the ready queue before the one that just finished its time slice.

	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.
A																			
B																			
C																			
D																			
E																			

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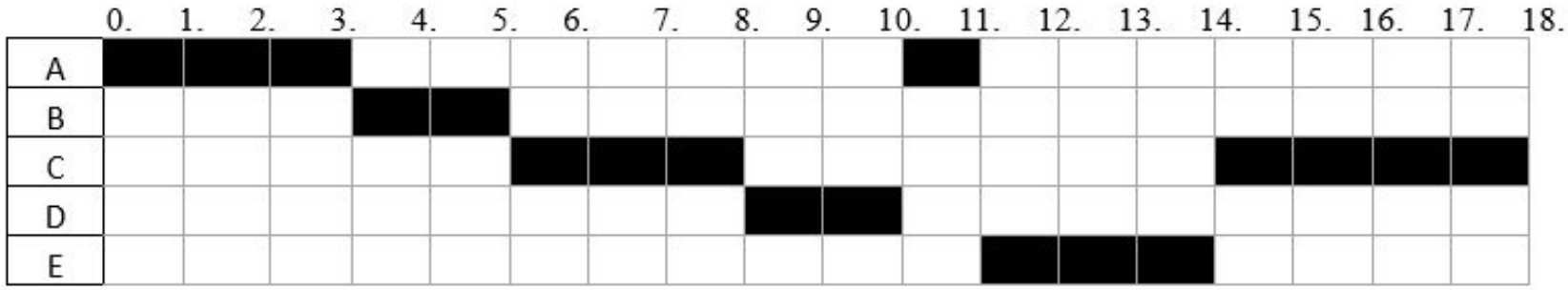


RR Variant: PennOS Scheduler

- In PennOS, you will have to implement a priority scheduler based mostly off of round robin.

- You will have 3 queues, each with a different priority (0, 1, 2)
  - Each queue acts like normal round robin within the queue

- You spend time quantum processing each queue proportional to the priority
  - Priority 0 is scheduled 1.5 times more often than priority 1
  - Priority 1 is scheduled 1.5 times more often than priority 2

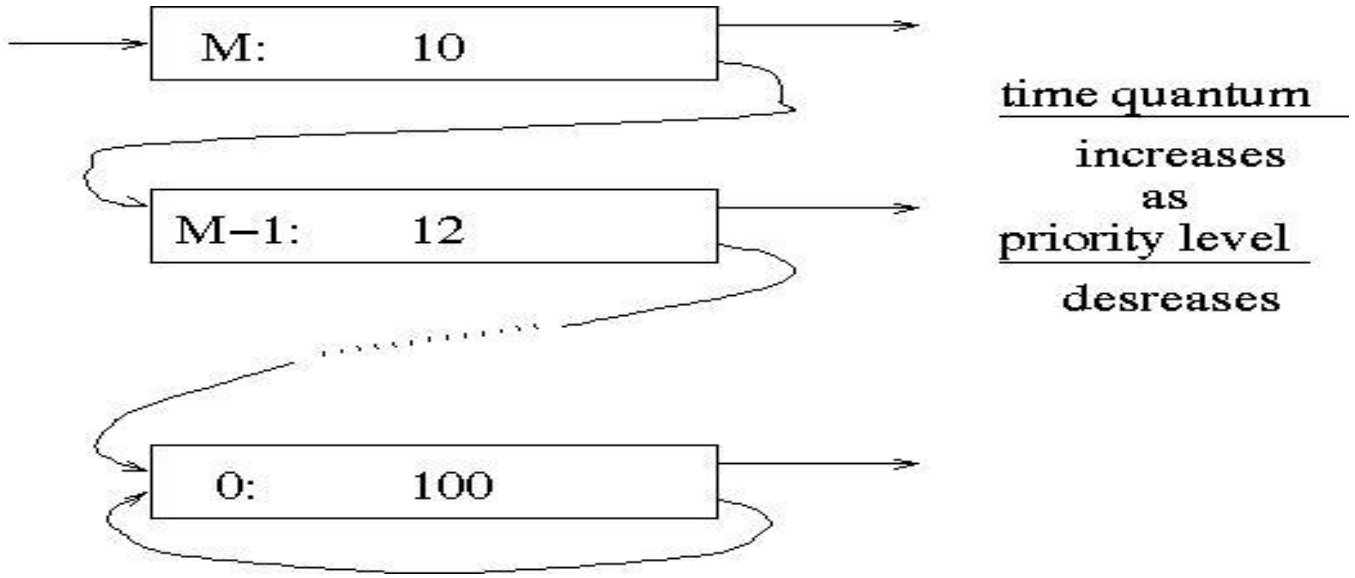
RR Variant: Priority Round Robin

- Same idea as round robin, but with multiple queues for different priority levels.
- Scheduler chooses the first item in the highest priority queue to run
- Scheduler only schedules items in lower priorities if all queues with higher priority are empty.

That's all!

- See you next time!

RR Variant: Multi Level Feedback



- Each priority level has a ready queue, and a time quantum
- Thread enters highest priority queue initially, and lower queue with each timer interrupt
- If a thread voluntarily stops using CPU before time is up, it is moved to the end of the current queue
- Bottom queue is standard Round Robin
- Thread in a given queue not scheduled until all higher queues are empty

Multi Level Feedback Analysis

- Threads with high I/O bursts are preferred
  - Makes higher utilization of the I/O devices
  - Good for interactive programs (keyboard, terminal, mouse is I/O)
- Threads that need the CPU a lot will sink to lower priority, giving shorter threads a chance to run
- Still have to be careful in choosing time quantum
- Also have to be careful in choosing how many layers

Multi Level Feedback Variants: Priority

- Can assign tasks different priority levels upon initiation that decide which queue it starts in
  - E.g. the scheduler should have higher priority than HelloWorld.java
- Update the priority based on recent CPU usage rather than overall cpu usage of a task
  - Makes sure that priority is consistent with recent behavior
- Many others that vary from system to system

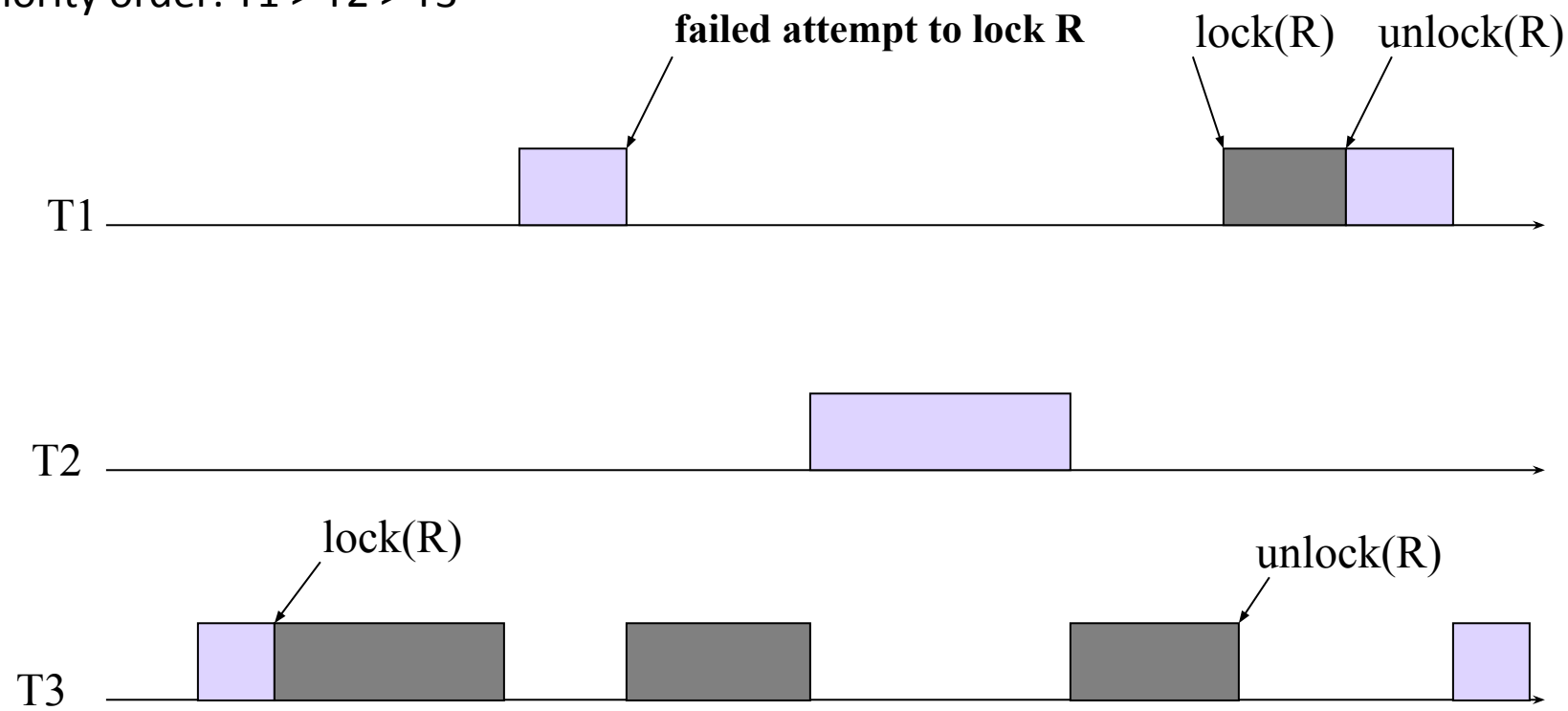
Why did we talk about this?

- Scheduling is fundamental towards how computer can multi-task
- This is a great example of how “systems” intersects with algorithms :)
- It shows up occasionally in the real world :)
  - Scheduling threads with priority with shared resources can cause a priority inversion, potentially causing serious errors.

What really happened on Mars Rover Pathfinder, Mike Jones.
http://www.cs.cornell.edu/courses/cs614/1999sp/papers/pathfinder.html

The Priority Inversion Problem

Priority order: T1 > T2 > T3



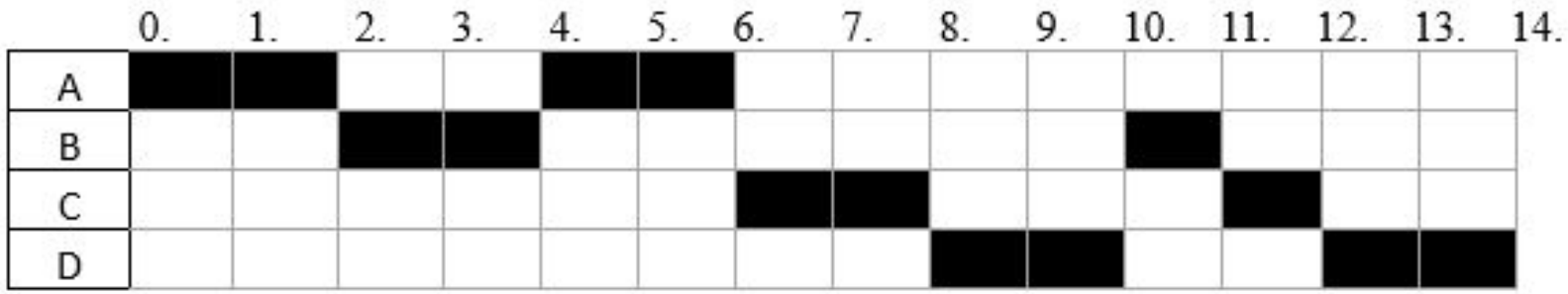
T2 is causing a higher priority task T1 wait !

More

- For those curious, there was a LOT left out
- RTOS (Real Time Operating Systems)
  - For real time applications
  - CRITICAL that data and events meet defined time constraints
  - Different focus in scheduling. Throughput is de-prioritized
- Fair-share scheduling
  - Equal distribution across different users instead of by processes
- Etc.

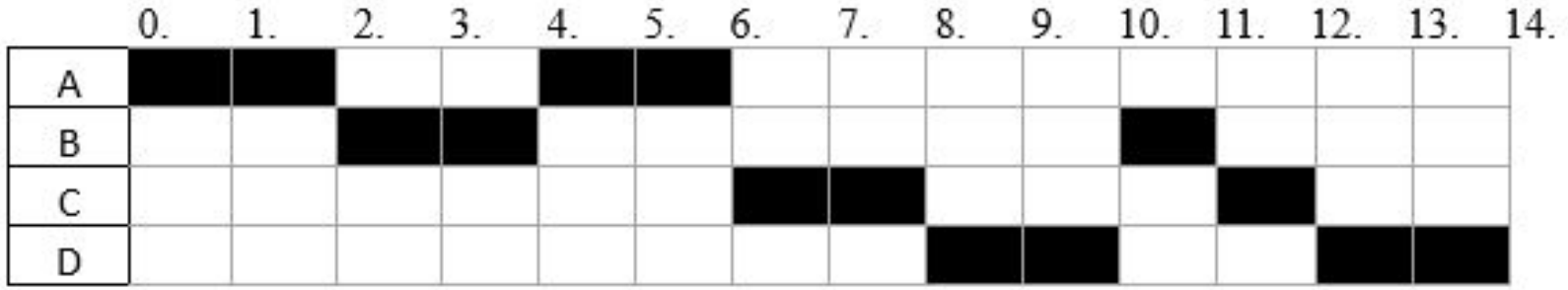
More Round Robin Practice

- Four processes are executing on one CPU following round robin scheduling:
- You can as



  - All processes do not block for I/O or any resource.
  - Context switching and running the Scheduler are instantaneous.
  - If a process arrives at the same time as the running process' time slice finishes, the one that just arrived goes into the ready queue before the one that just finished its time slice.

More Round Robin Practice



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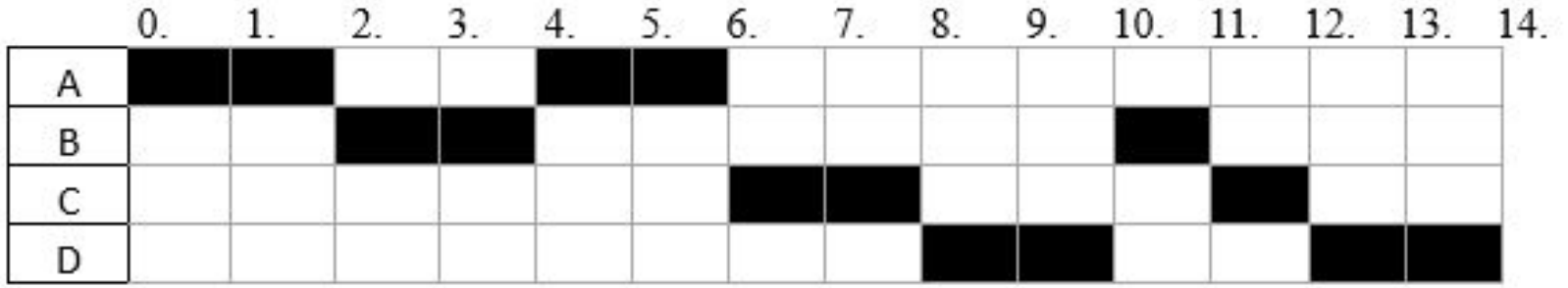
- If a process arrives at the same time as the running process' time slice finishes, the one that just arrived goes into the ready queue before the one that just finished its time slice.

- What is the earliest time that process C could have arrived?
- Which processes are in the ready queue at time 9?
- If this algorithm used a quantum of 3 instead of 2, how many fewer context switches would there be?

More Round Robin Practice



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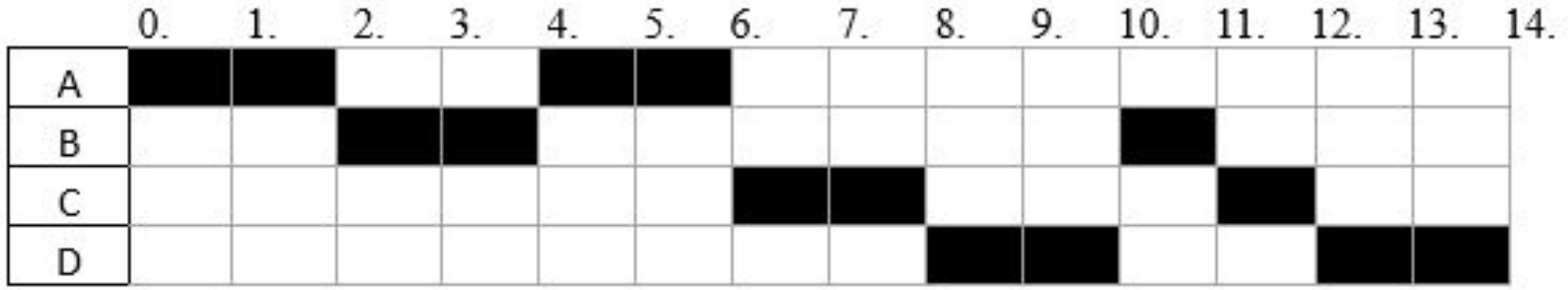
❖ What is the earliest time that process C could have arrived?

- If C arrived at time 0, 1, or 2, it would have run at time 4
- C could have shown up at time 3 and come after A in the queue
- C showed up at time 3 at earliest

More Round Robin Practice



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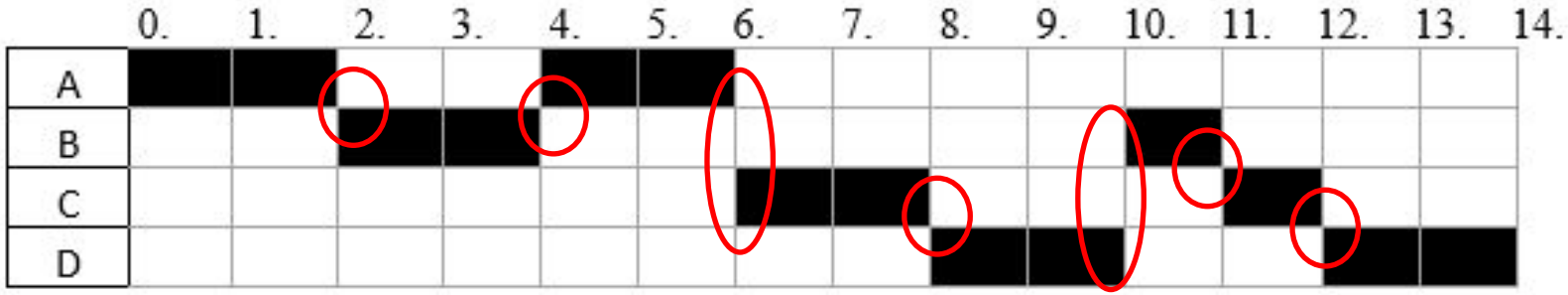
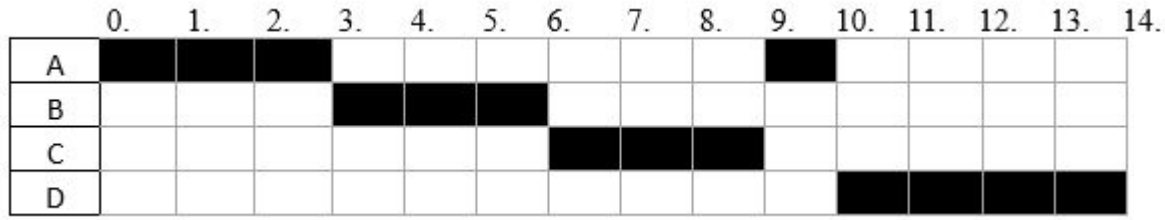
- Which processes are in the ready queue at time 9?
  - D is running, so it is not in the queue
  - A has finished
  - B and C still have to finish, so they are in the queue.

More Round Robin Practice

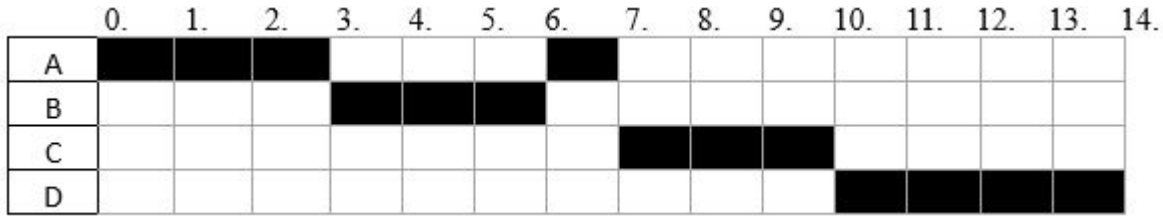


- If this algorithm used a quantum of 3 instead of 2, how many fewer context switches would there be?
  - Currently there are 7 context switches
  - If quantum was 3:

    Depends on if C shows up at time 3 or 4



  - Or:



Either way, only 4 context switches, so 3 less than quantum = 2