Lecture 13: Introduction to Concurrency

(Thread, Amdahl's Law, and CPU Scheduling)

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COP 4610 Operating Systems

Outline

- Threads
- Dispatcher
- Amdahl’s Law
- CPU Scheduling

Why *Concurrency*?

- Allows multiple applications to run at the same time
  - Analogy: juggling

- What is an applications?
  - A Program that runs on the OS.

History Phase I: Hardware Expensive, Humans Cheap

- Hardware: mainframes
- OS: human operators
  - Handle one ***job*** (a unit of processing) at a time
  - Computer time wasted while operators walk around the machine room

IBM System/360

OS Design Goal

- Efficient use of the hardware
  - ***Batch system***: collects a batch of jobs before processing them and printing out results
    - Job collection, job processing, and printing out results can occur concurrently
  - ***Multiprogramming***: multiple programs can run concurrently
    - Example: I/O-bound jobs and CPU-bound jobs

History Phase II: Hardware Cheap, Humans Expensive

- Hardware: terminals

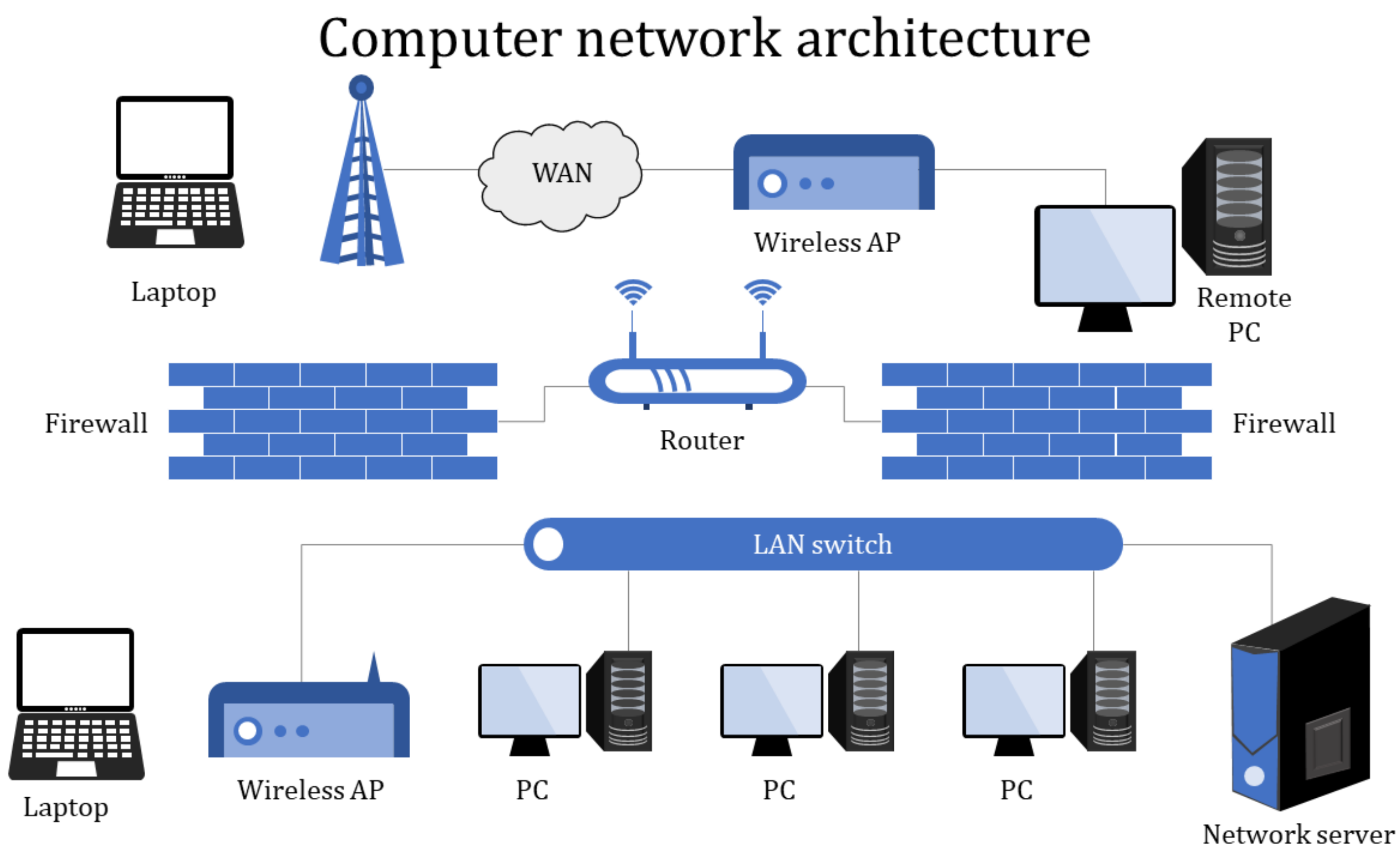
- OS design goal: more efficient use of human resources
  - ***Timesharing systems***: each user can afford to own terminals to interact with machines
  - The operating system could support multiple users simultaneously, each with their own terminal
  - Each user had an efficient and responsive experience, without the need for dedicated machines for each person

History Phase III: Hardware Very Cheap, Humans Very Expensive

- Hardware: personal computers
- OS design goal: allowing a user to perform many tasks at the same time
  - ***Multitasking***: a single user can run multiple programs on the same machine at the same time
  - ***Multiprocessing***: the ability to use multiple processors on the same machine

History Phase IV: Distributed Systems

- Hardware: computers with networks



Why *Concurrency*?

- Allows multiple applications to run at the same time
  - Analogy: juggling

- Program is a state machine.

- What is the red ball?
  - A State.

Benefits of Concurrency

- Better performance
  - One application uses only the processor
  - One application uses only the disk drive
  - Completion time is shorter when running both concurrently than consecutively

Drawbacks of Concurrency

- Applications need to be protected from one another
- Additional coordination mechanisms among applications
- Overhead to switch among applications
- Potential performance degradation when running too many applications

Thread

- A sequential execution stream
  - The smallest CPU scheduling unit
  - Can be programmed as if it owns the entire CPU
    - Implication: an infinite loop within a thread won’t halt the system
  - Illusion of multiple CPUs on a single-CPU machine

Thread Benefits

- Simplified programming model per thread
- Example: Microsoft Word
  - One thread for grammar check; one thread for spelling check; one thread for formatting; and so on…
  - Can be programmed independently
  - Simplifies the development of large applications

Address Space

- Contains all states necessary to run a program
  - Code, data, stack
  - Program counter
  - Register values
  - Resources required by the program
  - Status of the running program
- **A mechanism to protect one app from crashing another app**

Process

- An address space + at least one thread of execution
  - Address space offers protection among processes
  - Threads offer concurrency
- A fundamental unit of computation

Process =? Program

- ***Program***: a collection of statements in C or any programming languages
- Process: a running instance of the program, with additional states and system resources

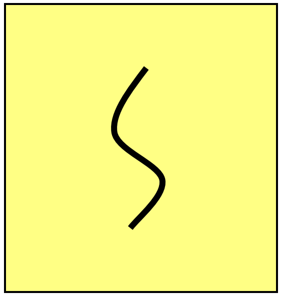
- Two processes can run the same program
  - The code segment of two processes are the same program

- A program can create multiple processes
  - Example: gcc, chrome

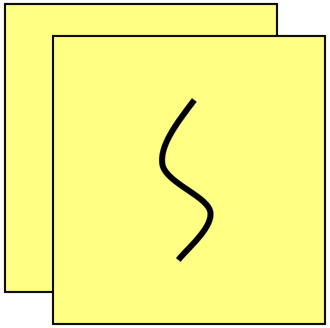
Real-life Analogy?

- Program: a recipe
- Process: everything needed to cook
  - e.g., kitchen
- Two chefs can cook the same recipe in different kitchens
- One complex recipe can involve several chefs

Some Definitions

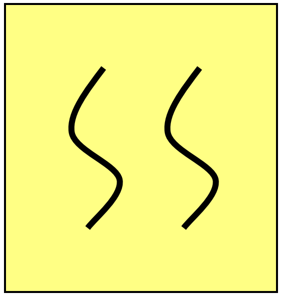


- *Uniprogramming*: running one process at a time
- *Multiprogramming*: running multiple processes on a machine



Some Definitions

- ***Multithreading***: having multiple threads per address space (threads share the same address space)
- ***Multiprocessing***: running programs on a machine with multiple processors
- ***Multitasking***: a single user can run multiple processes



Classifications of OSes

	Single address space	Multiple address spaces
Single thread	MS DOS, Macintosh	Traditional UNIX
Multiple threads	Embedded systems	Windows, iOS

Threads & Thread Control Block

- A thread owns a ***thread control block***
  - Execution states of the thread
  - The status of the thread
    - Running or sleeping
  - Scheduling information of the thread
    - e.g., priority

Threads & Dispatching Loop

- Threads are run from a ***dispatching loop***
  - Can be thought as a per-CPU thread
  - LOOP
    - Run thread
    - Save states
    - Choose a new thread to run
    - Load states from a different thread

Context switch

Scheduling

Simple? Not quite…

- How does the dispatcher regain control after a thread starts running?
- What states should a thread save?
- How does the dispatcher choose the next thread?

How does the dispatcher regain control?

- Two ways:
  1. Internal events ("Sleeping Beauty")
     - Yield—a thread gives up CPU voluntarily
       - A thread is waiting for I/O
       - A thread is waiting for some other thread
  2. External events
     - Interrupts—a complete disk request
     - Timer—it's like an alarm clock

What states should a thread save?

- Anything that the next thread may trash before a context switch
  - Program counter
  - Registers
  - Changes in execution stack

How does the dispatcher choose the next thread?

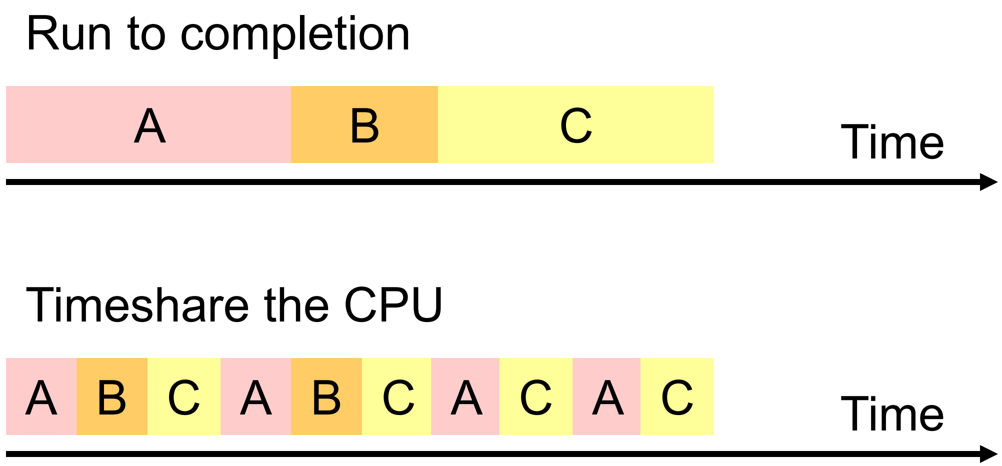
- The dispatcher keeps a list of threads that are ready to run
- If no threads are ready
  - Dispatcher just loops
- If one thread is ready
  - Easy

How does the dispatcher choose the next thread?

- If more than one thread are ready
  - We choose the next thread based on the scheduling policies
  - Examples
    - FIFO (first in, first out)
    - LIFO (last in, first out)
    - Priority-based policies

How does the dispatcher choose the next thread?

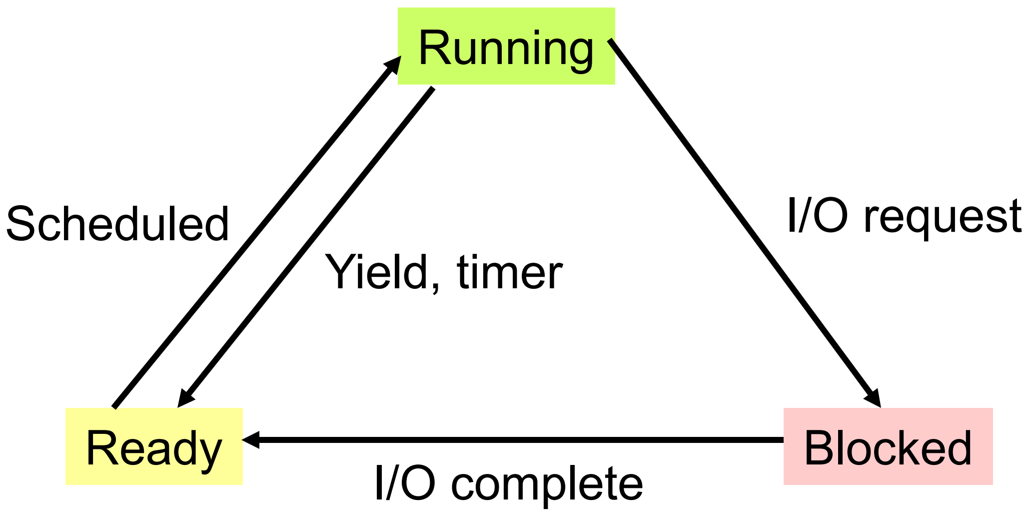
- Additional control by the dispatcher on how to share the CPU
  - Suppose we have three threads



Per-thread States

- Each thread can be in one of the three states
  1. ***Running***: has the CPU
  2. ***Blocked***: waiting for I/O or another thread
  3. ***Ready to run***: on the ready list, waiting for the CPU

Per-thread State Diagram



Important

For Multi-core Machines

- Each core has a dispatcher loop
  - Decide which thread will execute next
- One core has a global dispatcher loop
  - Decide which core to execute a thread

Parallelism vs. Concurrency

- *Parallel* computations
  - Computations can happen at the same time on separate cores
- *Concurrent* computations
  - One unit of computation does not depend on another unit of computation
    - Can be done in parallel on multiple cores
    - Can time share a single core (not parallel)

Real-life Example

- Two hands are playing piano in parallel (not concurrently)
  - Notes from left and right hands are dependent on each other
- Two separate groups singing ‘row row row your boat’ concurrently (and in parallel)

Amdahl's Law

- Identifies potential performance gains from adding cores
  - P = % of program that can be executed in parallel
  - N = number of cores
- $speedup \leq \frac{1}{(1-P)+\frac{P}{N}}$

Important

Amdahl’s Law

- Example
  - P = 75% of program that can be executed in parallel
  - N = 2 cores
- $speedup \leq \dfrac{1}{(1-0.75) + \dfrac{0.75}{2}}$ = 1.6

CPU Scheduler

- A ***CPU scheduler*** is responsible for
  - Removal of running process from the CPU
  - Selection of the next running process
    - Based on a particular strategy

Goals for a Scheduler

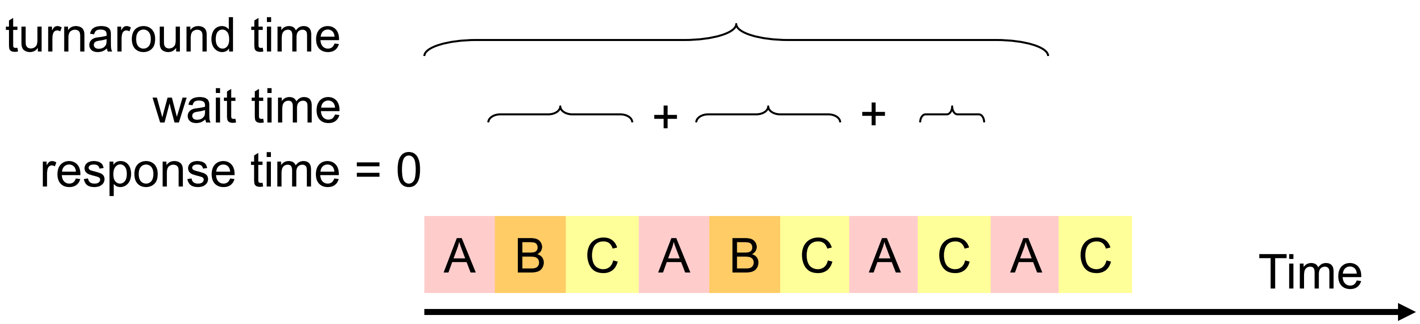
- Maximize
  - *CPU utilization*: keep the CPU as busy as possible
  - *Throughput*: the number of processes completed per unit time

Goals for a Scheduler

- Minimize
  - *Response time*: the time of submission to the time the first response is produced
  - *Wait time*: total time spent waiting in the ready queue
  - *Turnaround time*: the time of submission to the time of completion

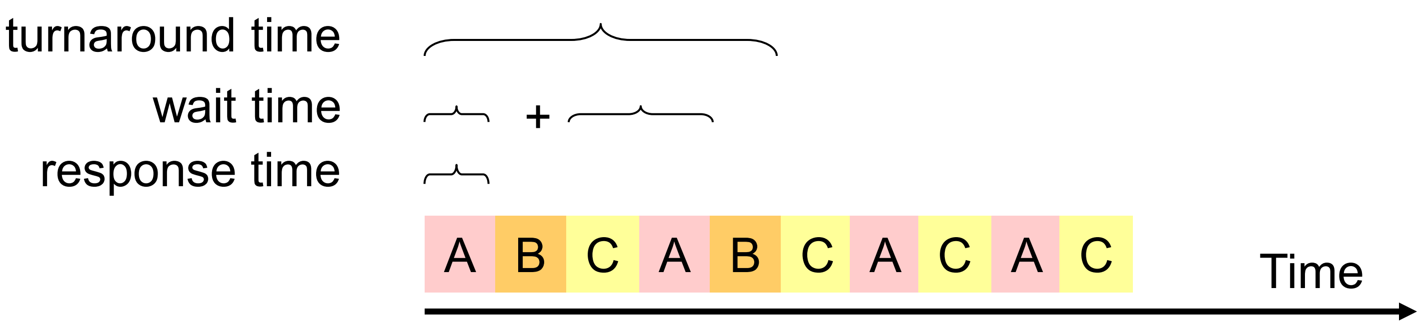
Goals for a Scheduler

- Suppose we have processes A, B, and C, submitted at time 0
- We want to know the response time, wait time, and turnaround time of process A



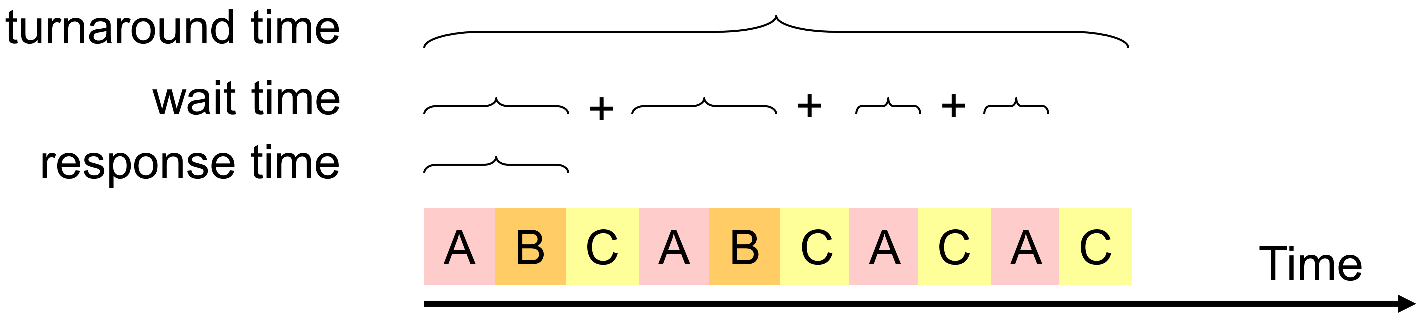
Goals for a Scheduler

- Suppose we have processes A, B, and C, submitted at time 0
- We want to know the response time, wait time, and turnaround time of process B



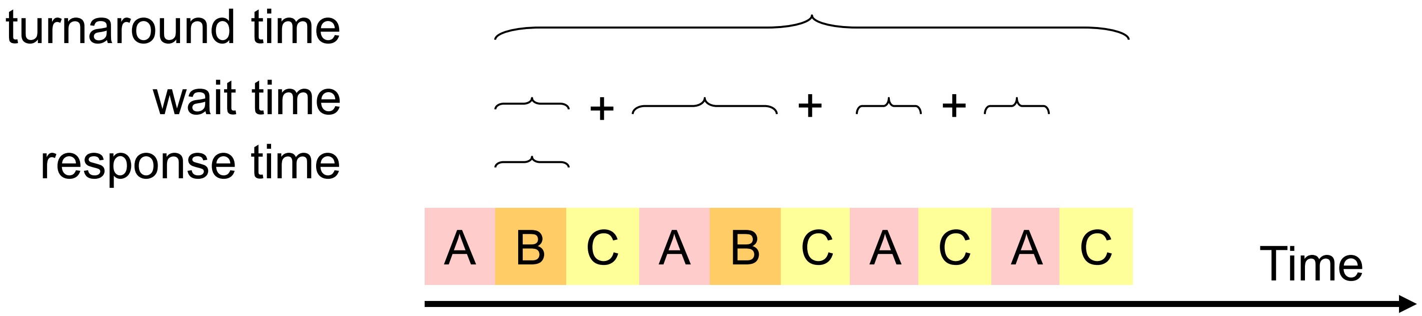
Goals for a Scheduler

- Suppose we have processes A, B, and C, submitted at time 0
- We want to know the response time, wait time, and turnaround time of process C



Goals for a Scheduler

- Suppose we have processes A and B submitted at time 0; process C, time 1
- We want to know the response time, wait time, and turnaround time of process C



Goals for a Scheduler

- Achieve *fairness*
  - What is fair?
    - Guaranteed to have at least 1/n share
    - How do two people divide a cake in a fair way?
- There are tensions among these goals

Assumptions

- Each user runs one process
- Each process is single threaded
- Processes are independent

- They are not realistic assumptions; they serve to simplify analyses

Scheduling Policies

- FIFO (first in, first out)
- Round robin
- SJF (shortest job first)
- Multilevel feedback queues
- Lottery scheduling

FIFO

- ***FIFO***: assigns the CPU based on the order of requests
  - ***Nonpreemptive***: A process keeps running on a CPU until it is blocked or terminated
  - Also known as FCFS (first come, first serve)

  \+ Simple

  \- Short jobs can get stuck behind long jobs

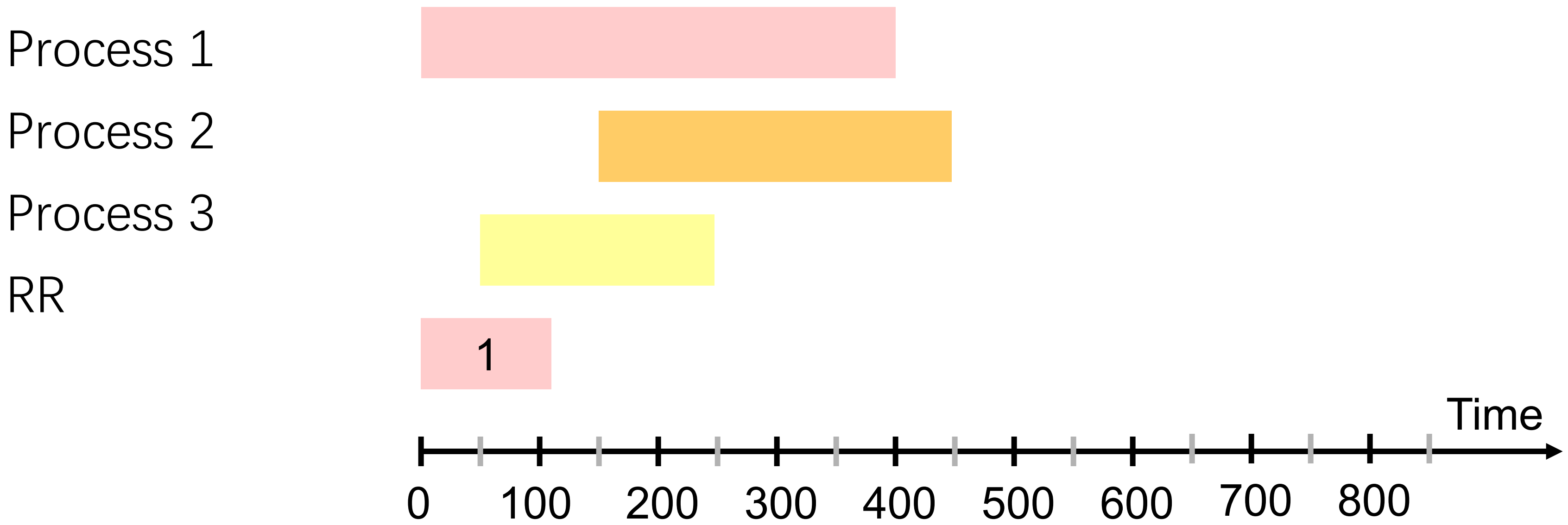
Round Robin

- *Round Robin (RR)* periodically releases the CPU from long-running jobs
  - Based on timer interrupts so short jobs can get a fair share of CPU time
  - *Preemptive*: a process can be forced to leave its running state and replaced by another running process
  - *Time slice*: interval between timer interrupts

More on Round Robin

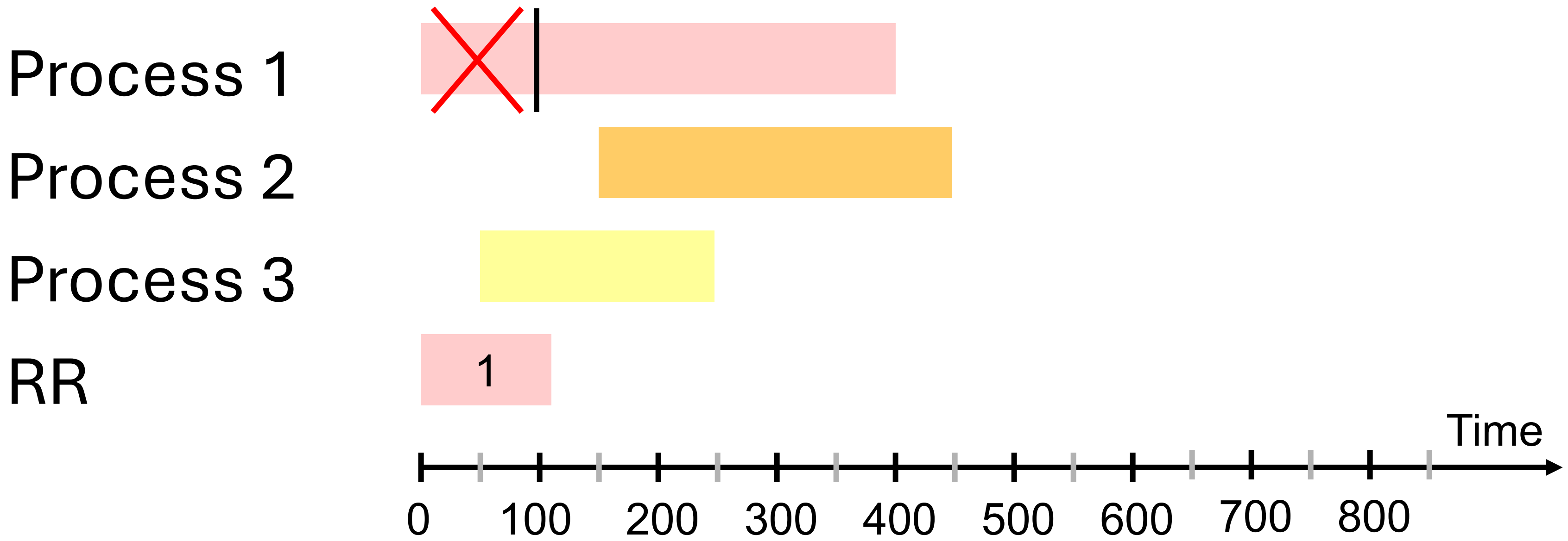
- If time slice is too long
  - Scheduling degrades to FIFO
- If time slice is too short
  - Throughput suffers
  - Context switching cost dominates

Round Robin (Time slice = 100)



Important

Round Robin (Time slice = 100)



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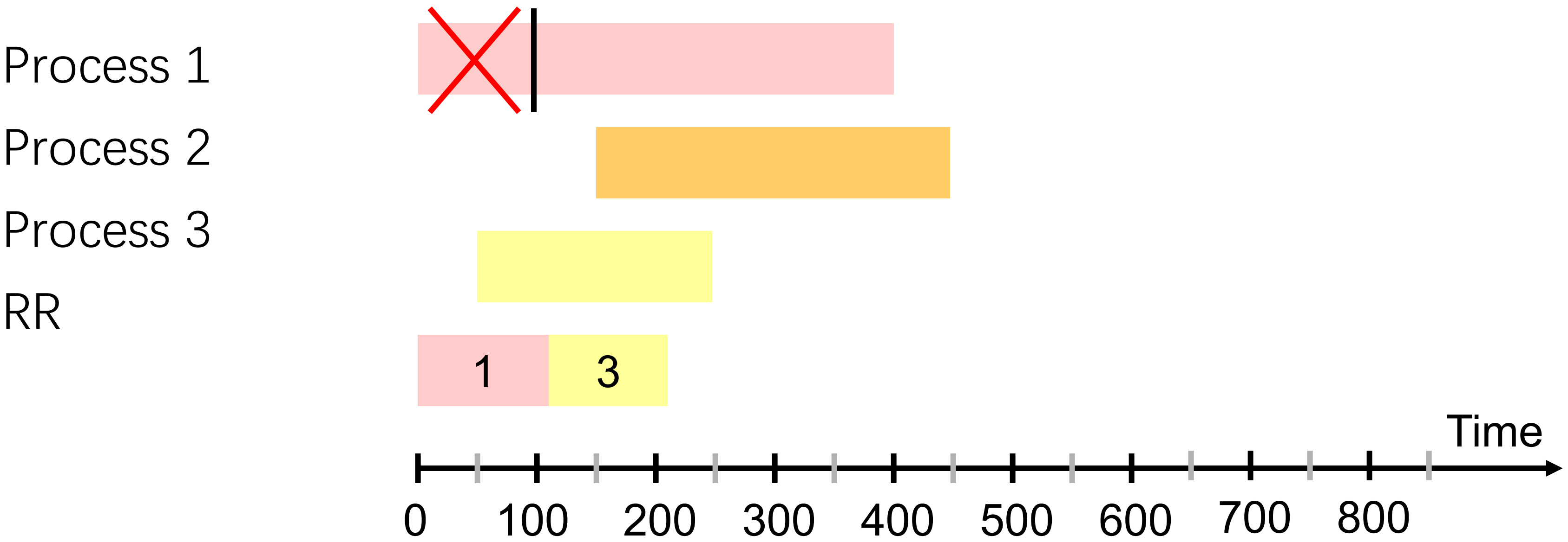

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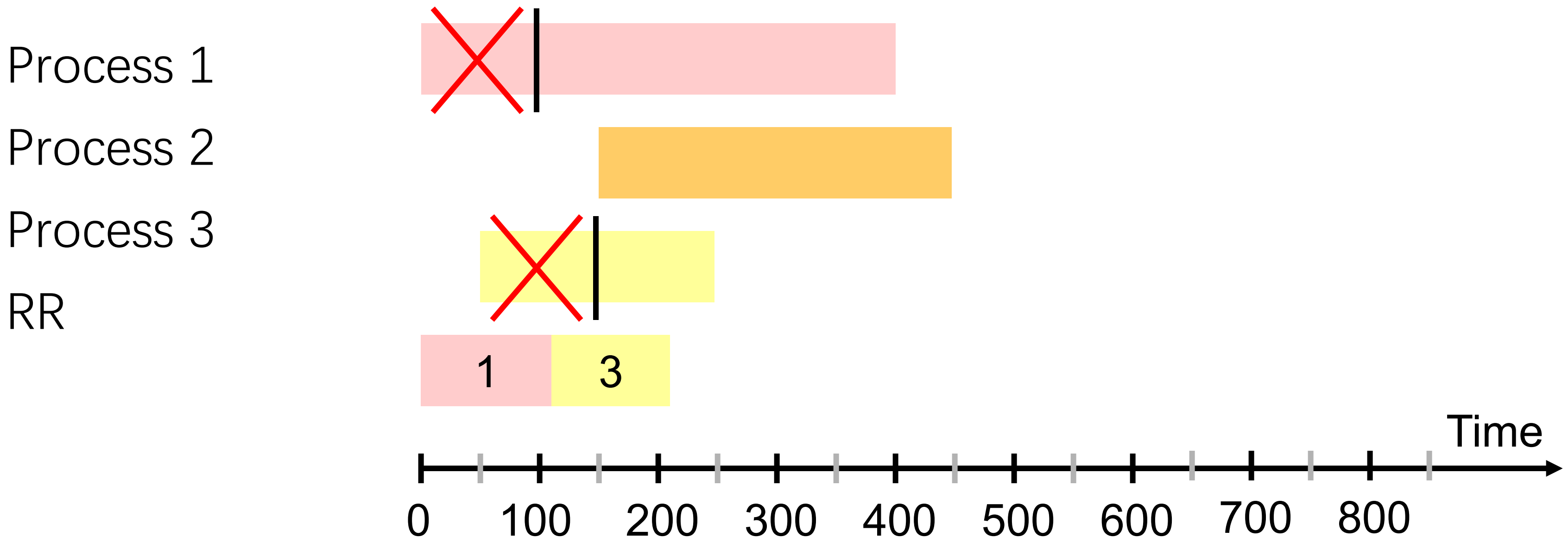

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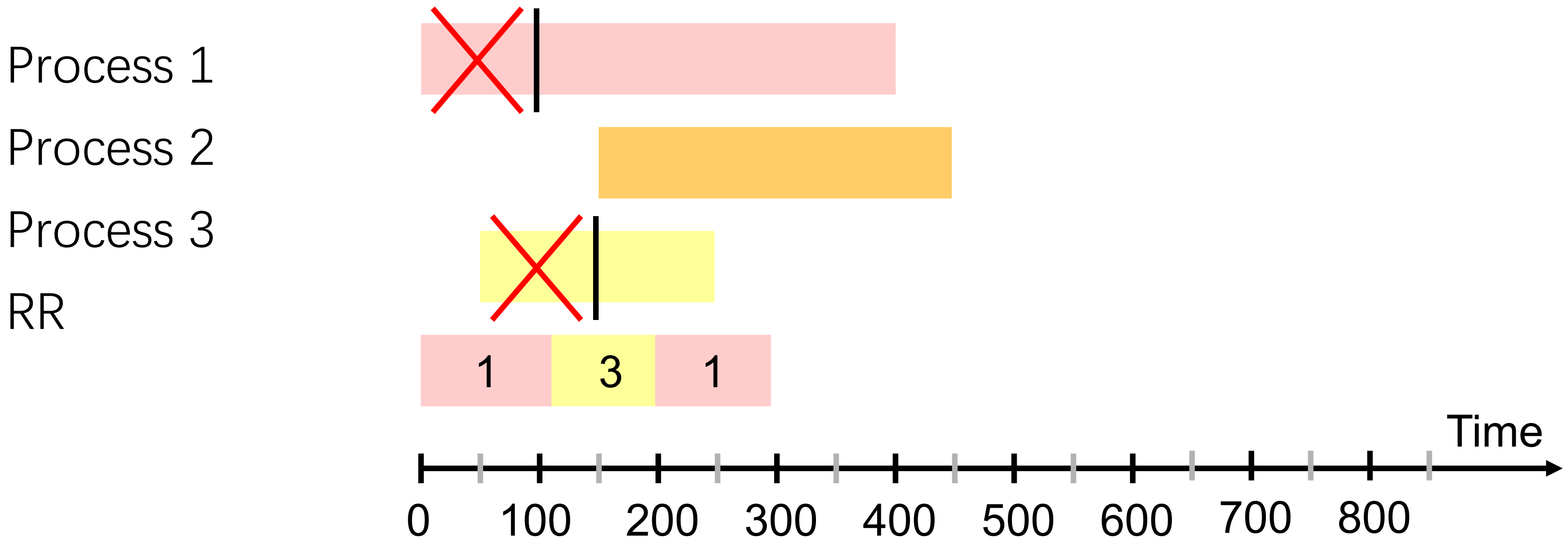

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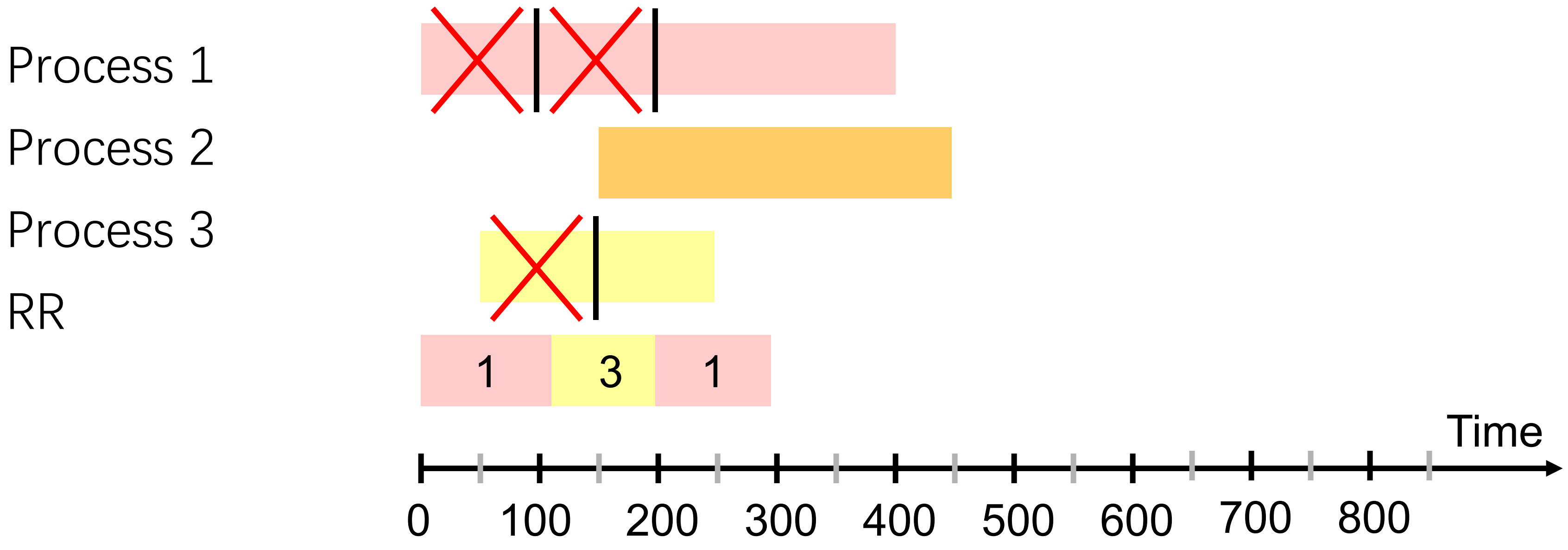

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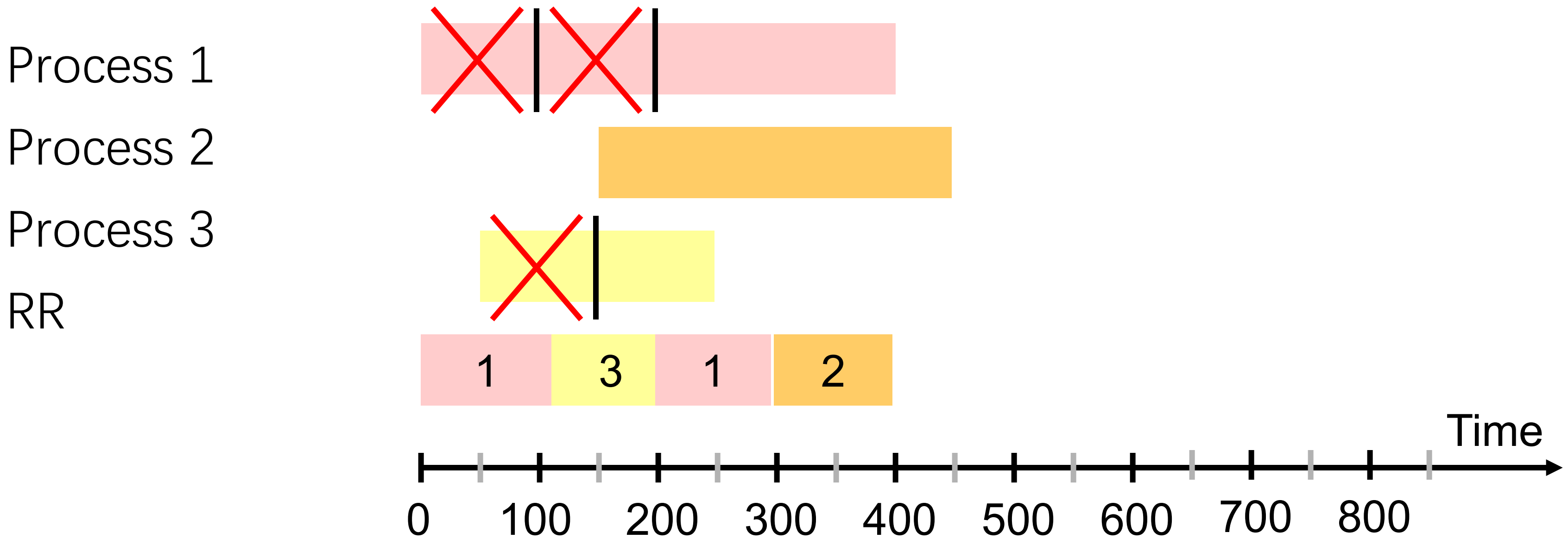

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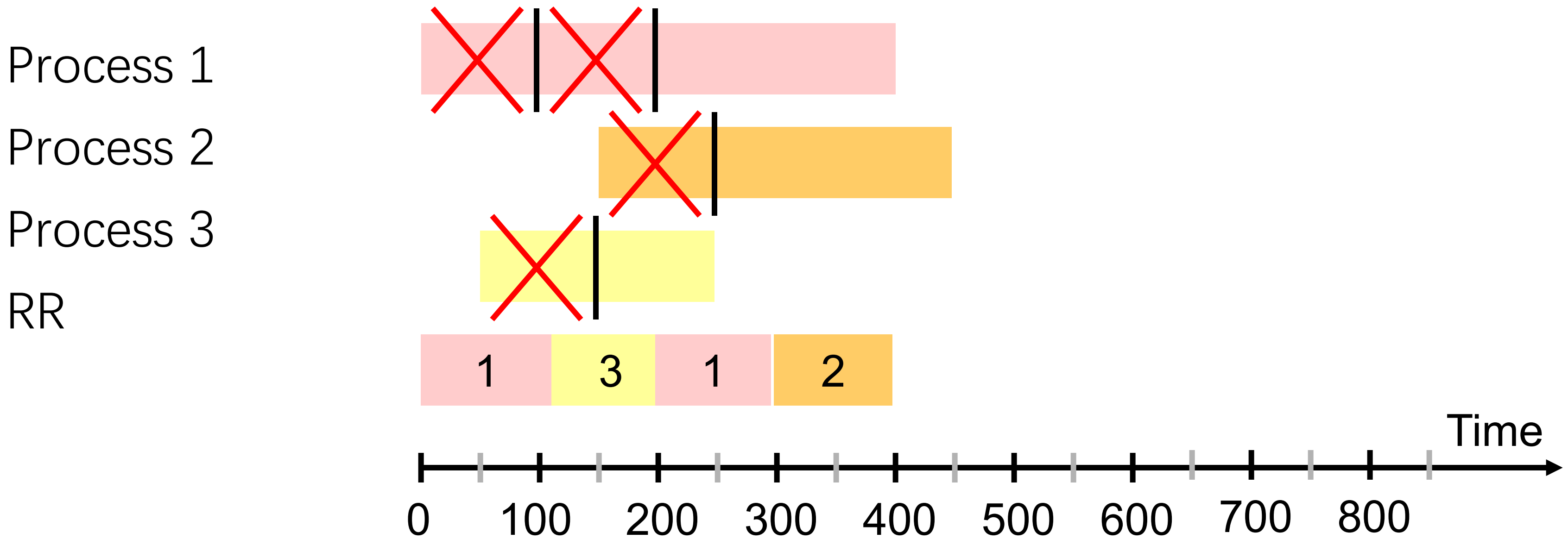

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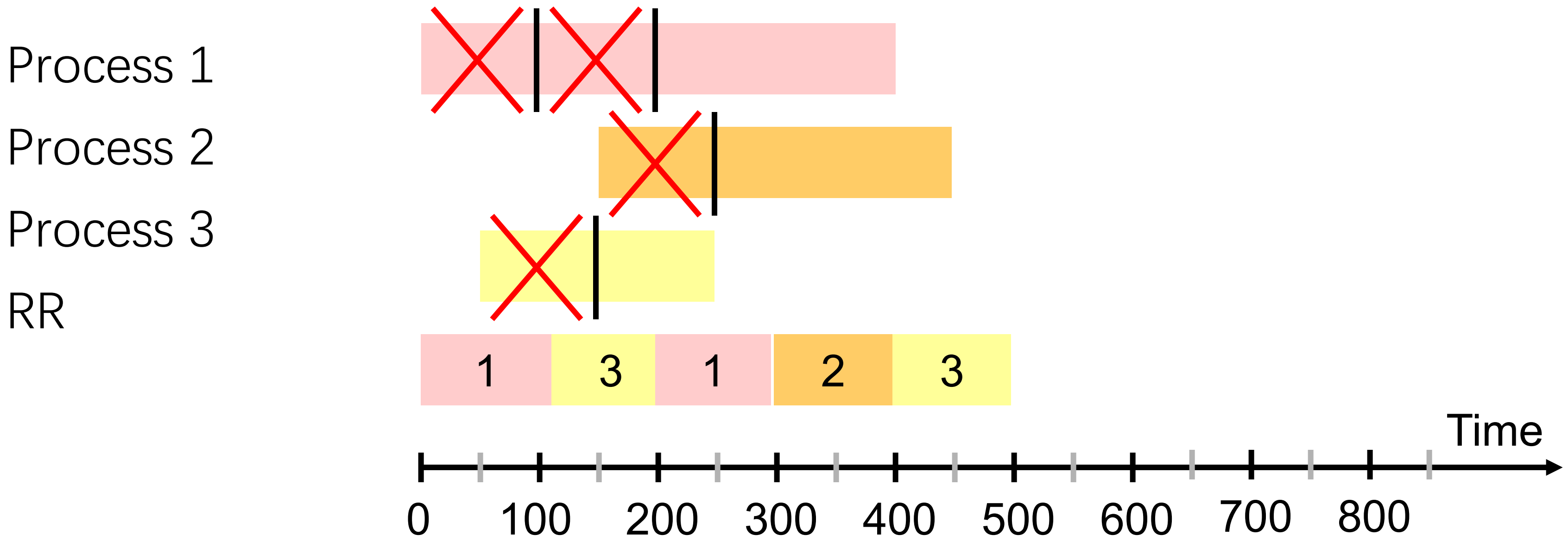

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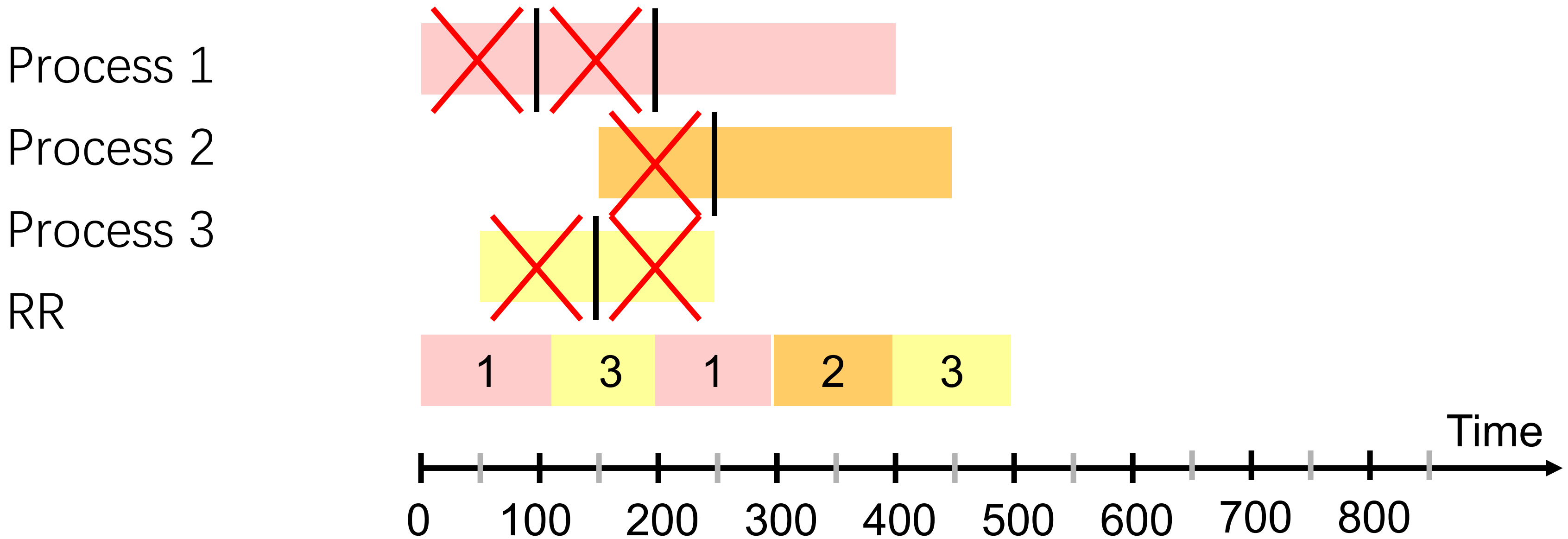
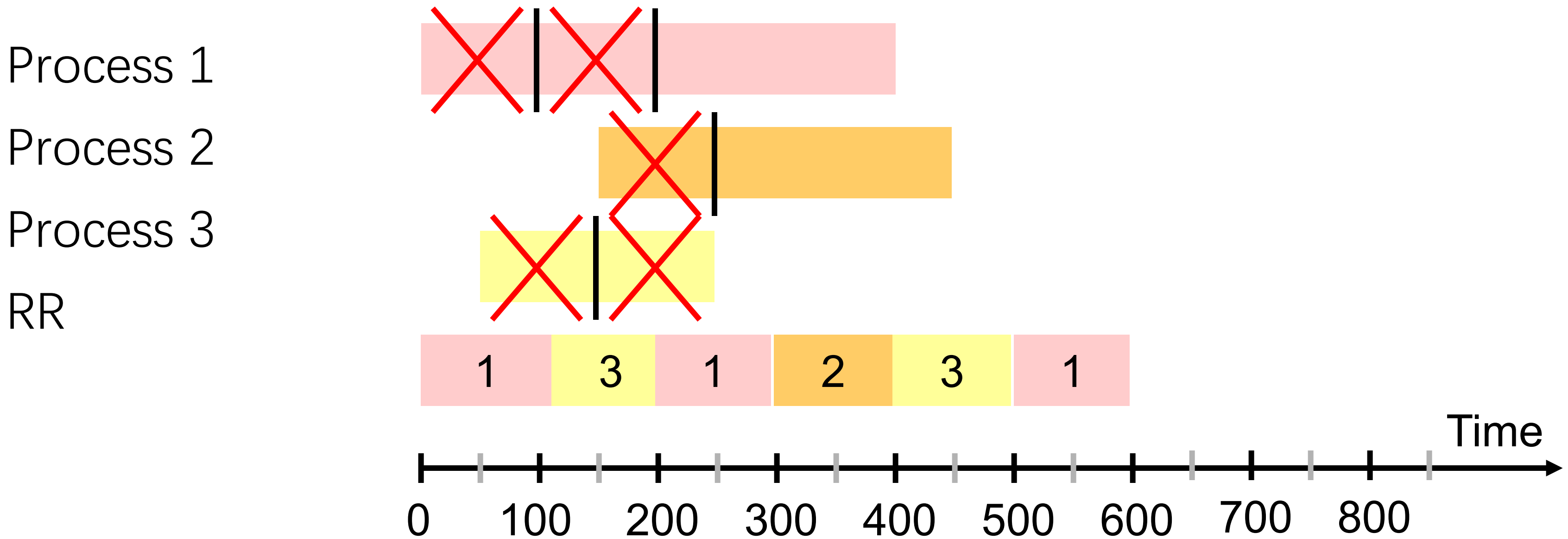
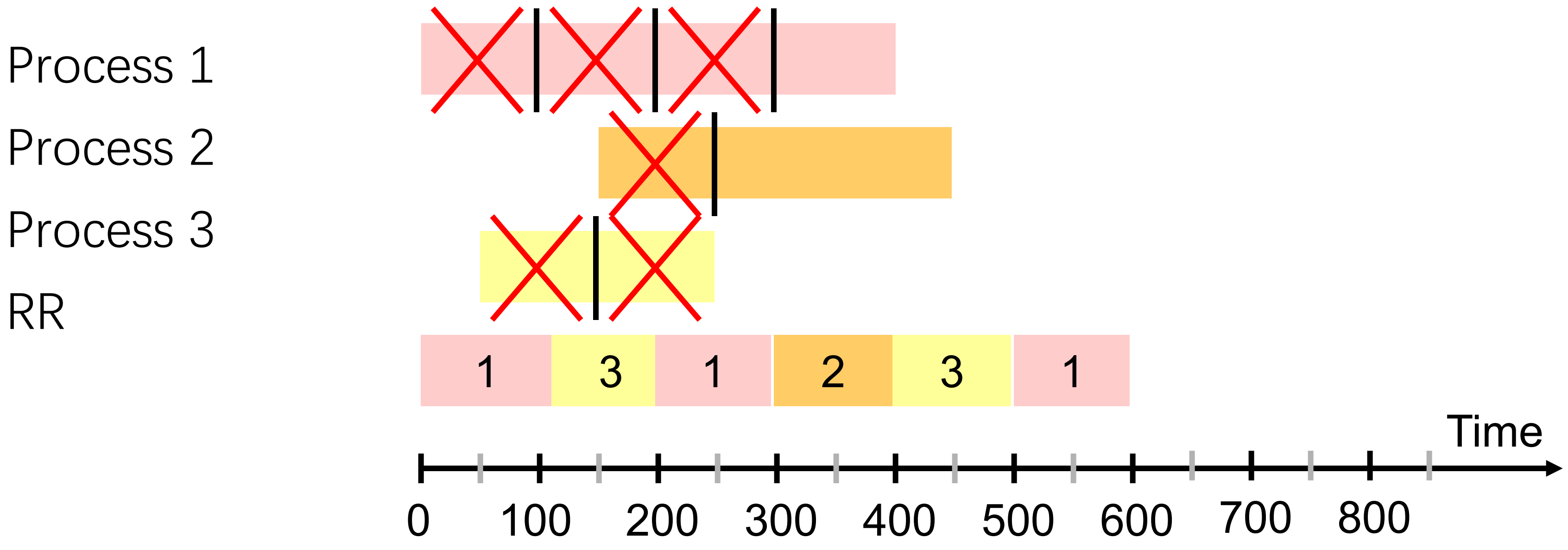


Round Robin (Time slice = 100)



Round Robin (Time slice = 100)



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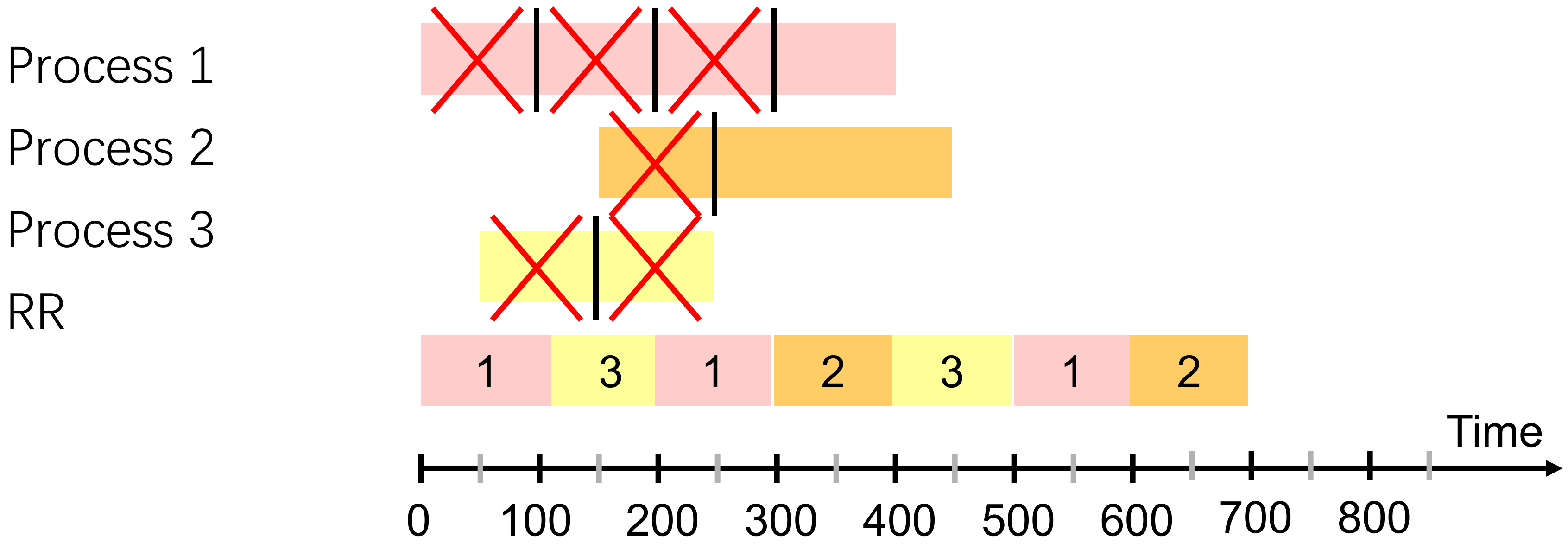

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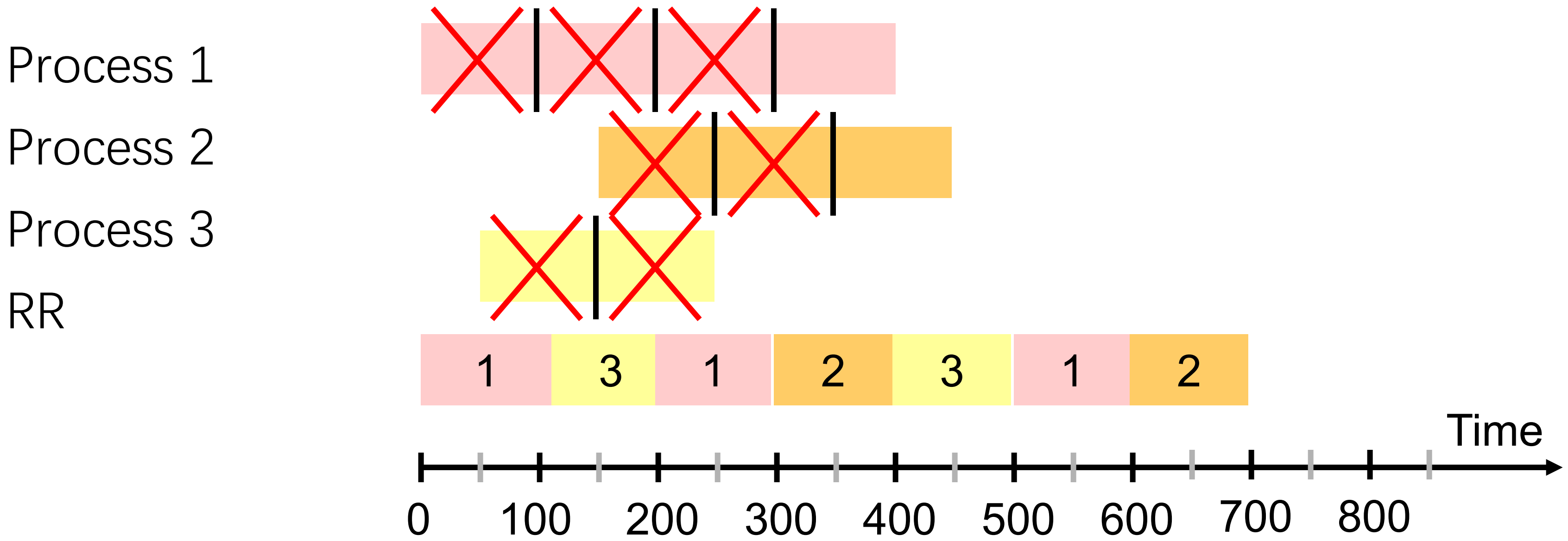

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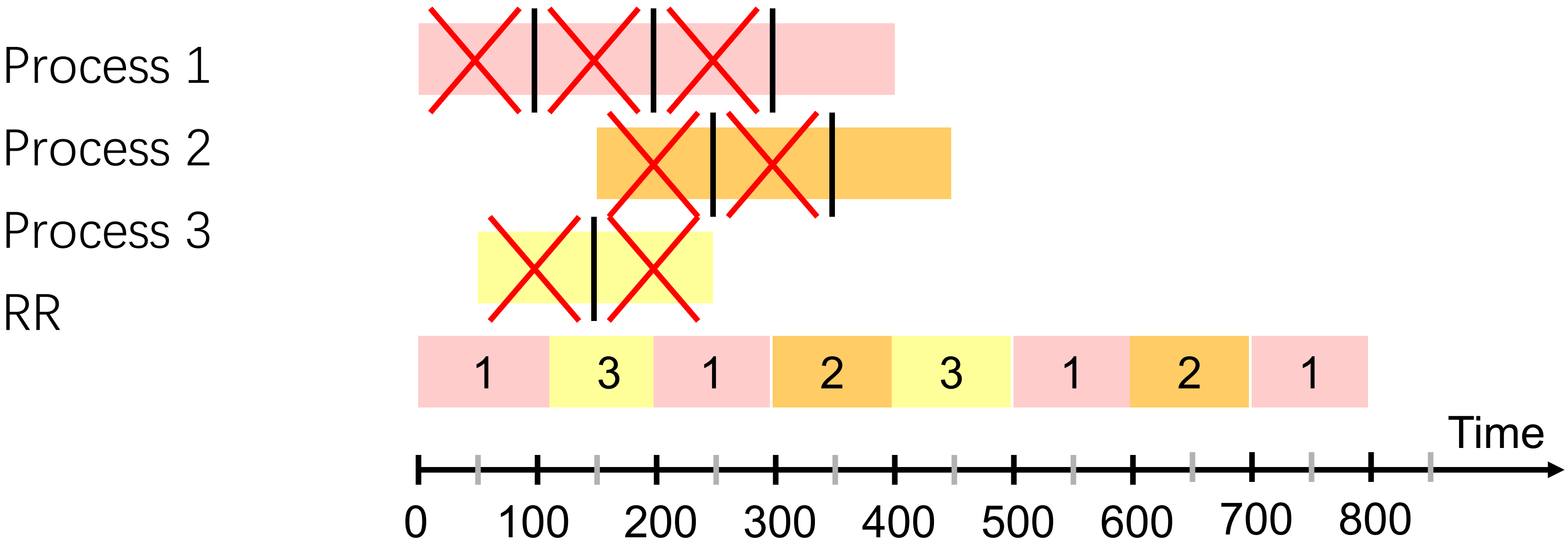

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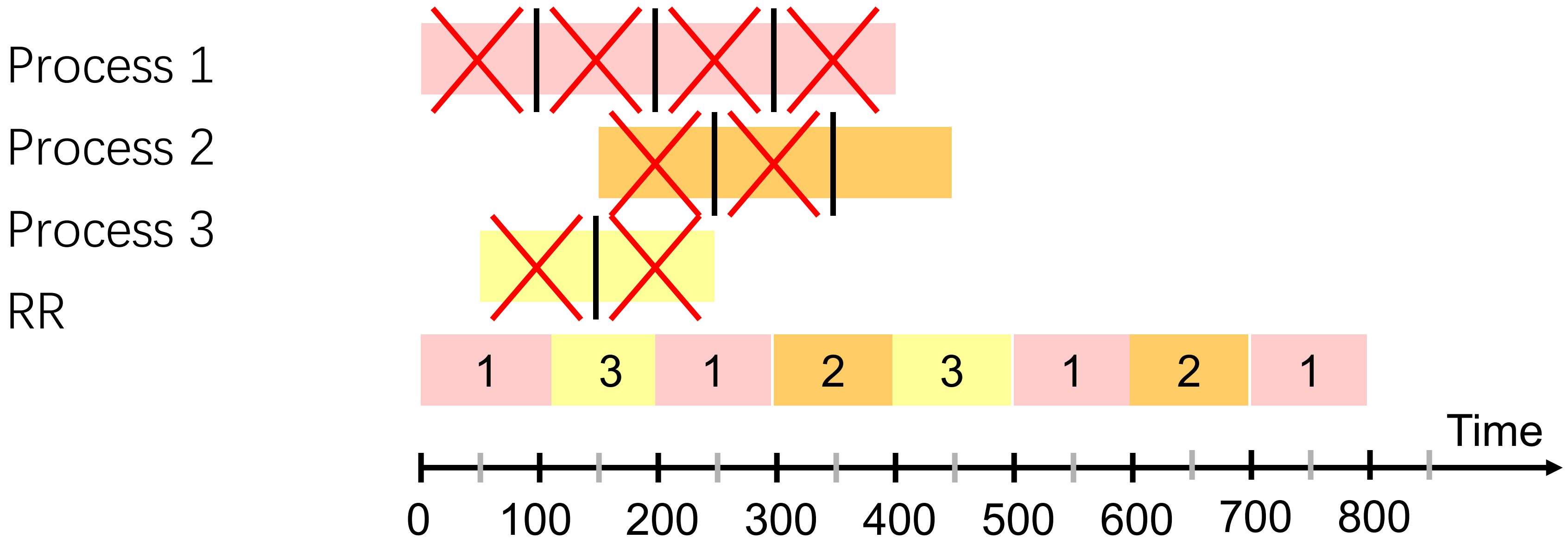

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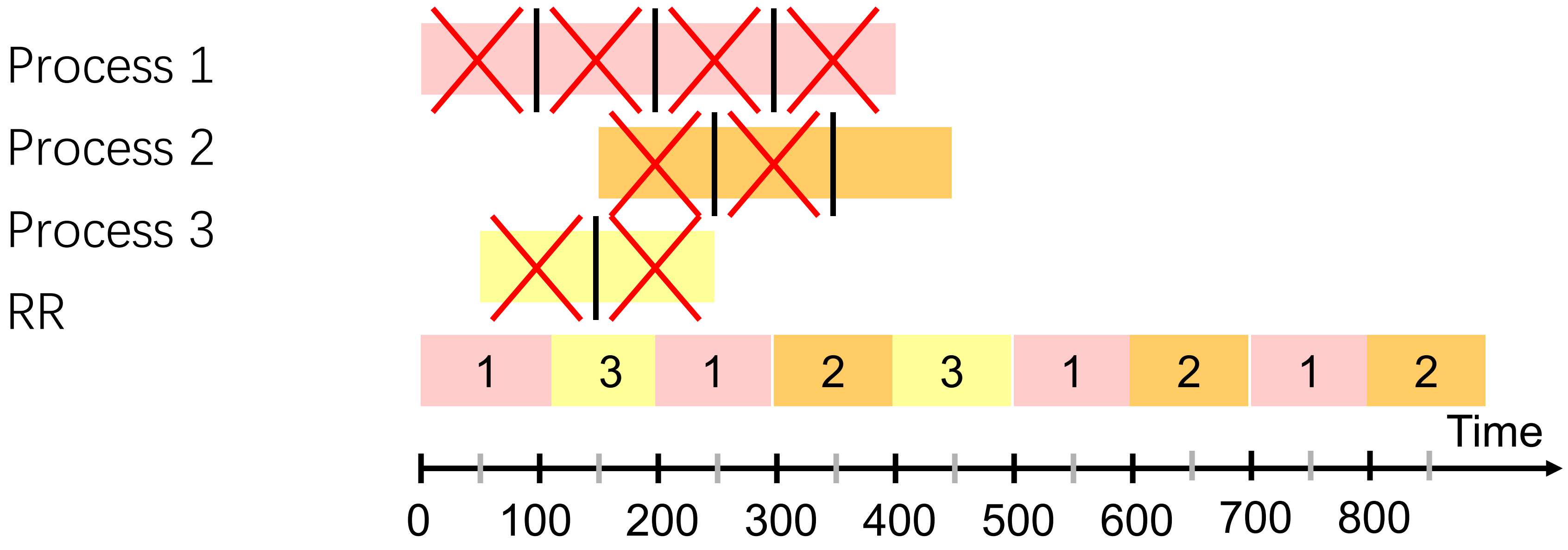

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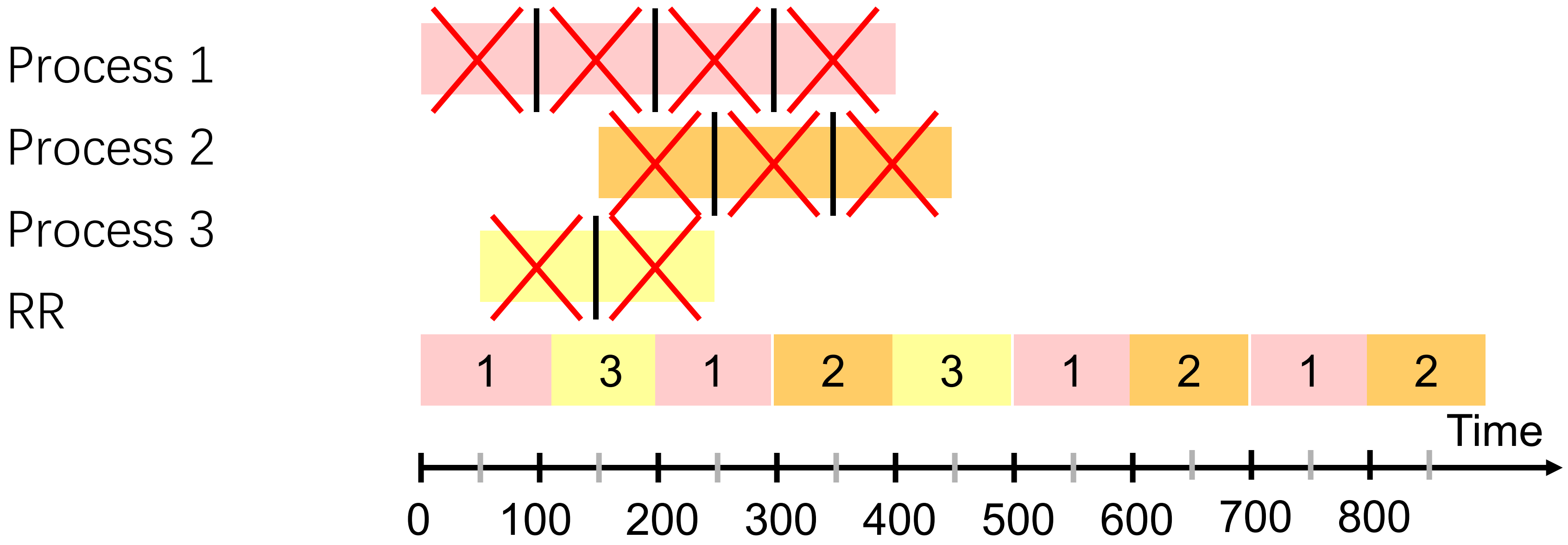
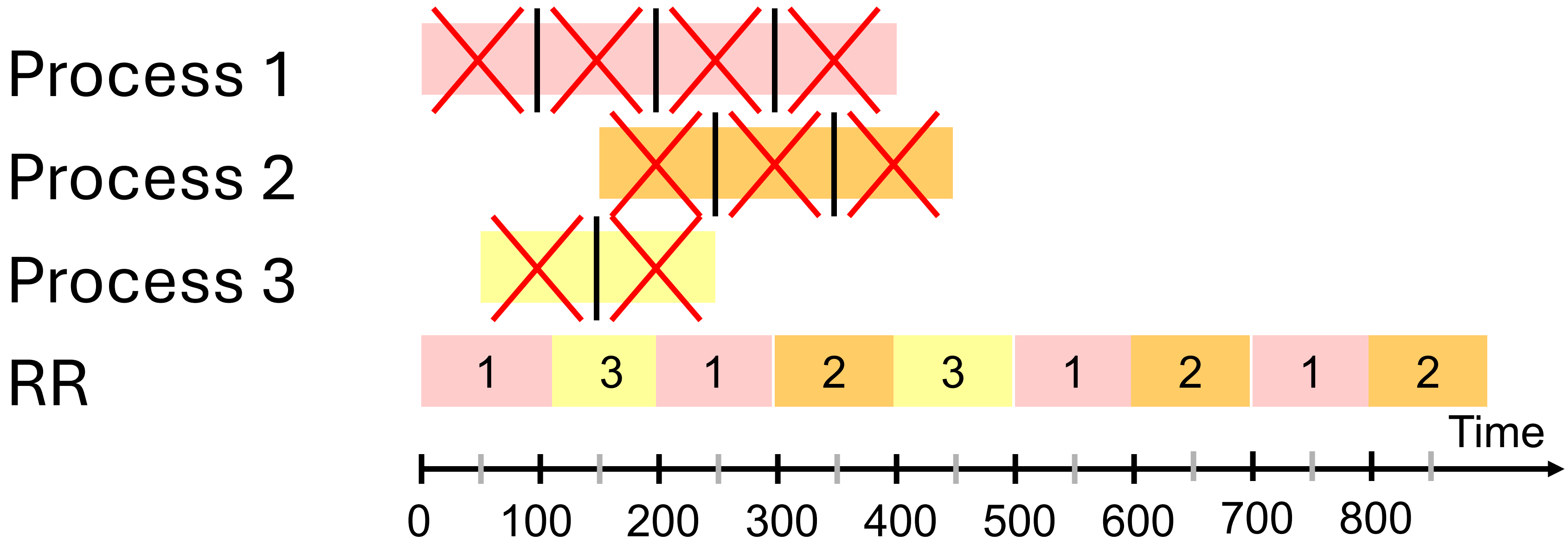


Round Robin (Time slice = 100)

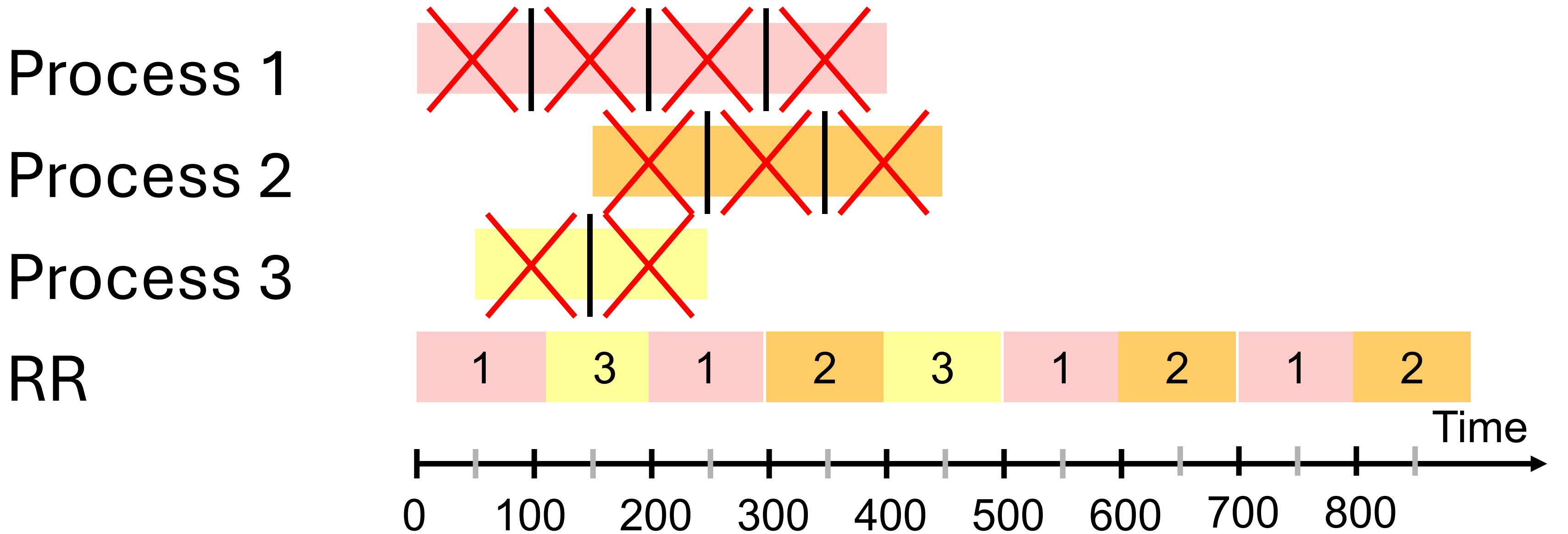


Response time for process 1: 0

Response time for process 2: 300 – 150 = 150

Response time for process 3: 100 – 50 = 50

Round Robin (Time slice = 100)

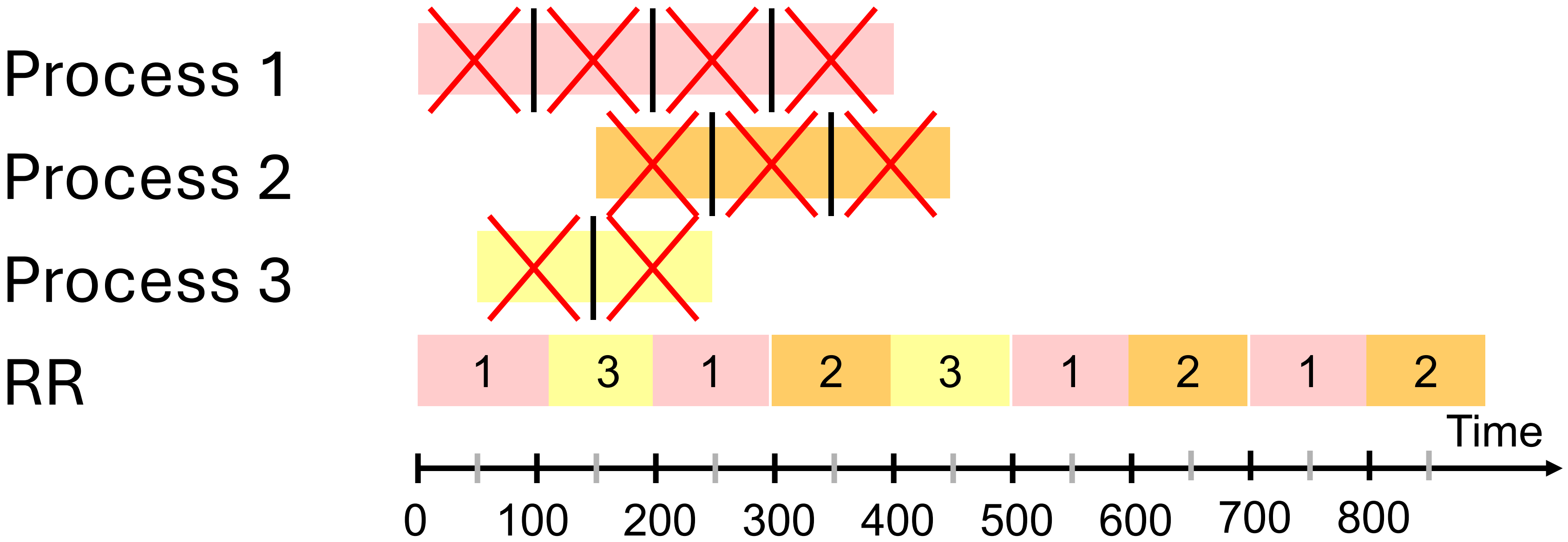


Wait time for process 1: 0 + (200 – 100) + (500 – 300) + (700 - 600) = 400

Wait time for process 2: (300 – 150) + (600 – 400) + (800 – 700) = 450

Wait time for process 3: (100 - 50) + (400 – 200) = 250

Round Robin (Time slice = 100)



Turnaround time for process 1: 800 – 0 = 800

Turnaround time for process 2: 900 – 150 = 750

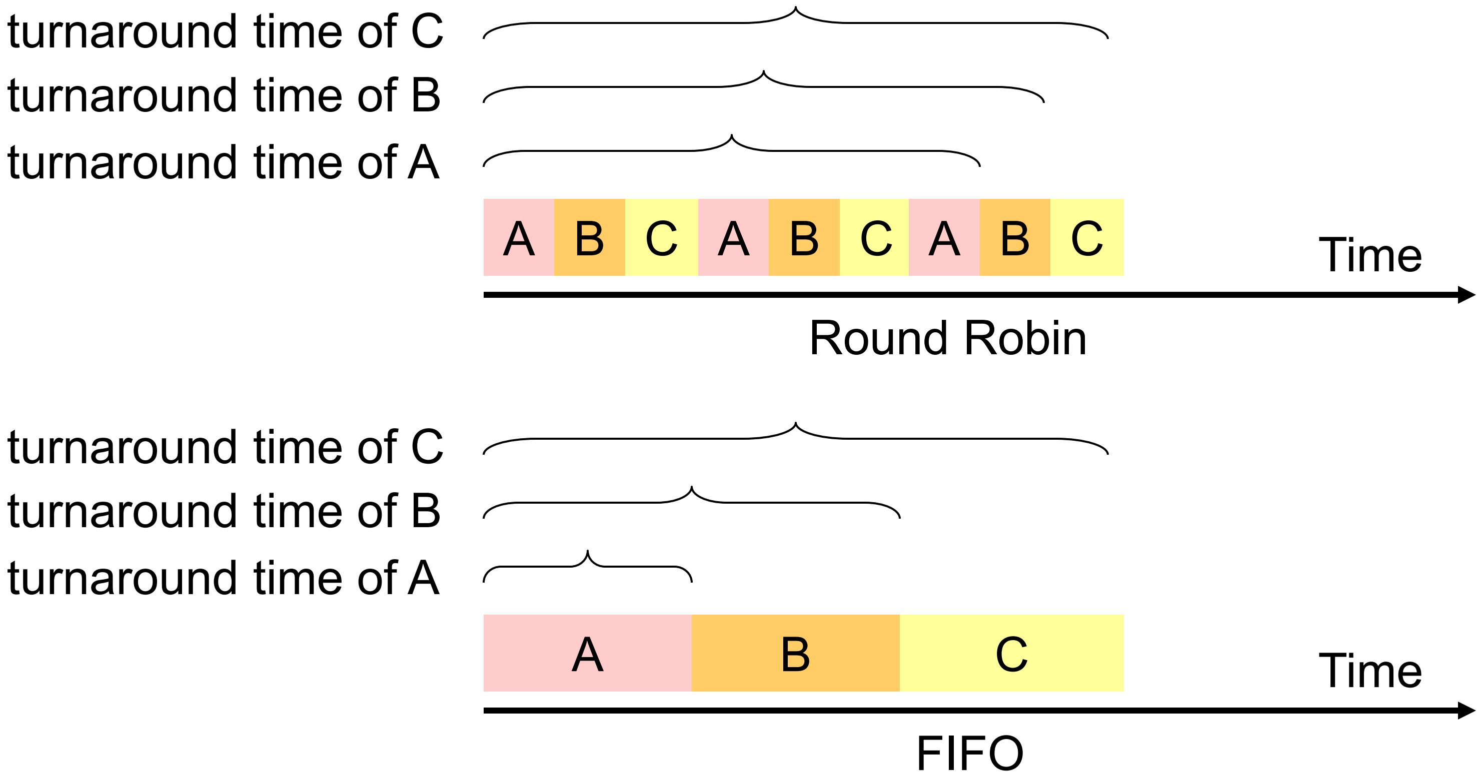
Turnaround time for process 3: 500 – 50 = 450

FIFO vs. Round Robin

- With zero-cost context switch, is RR always better than FIFO?

FIFO vs. Round Robin

- Suppose we have three jobs of equal length



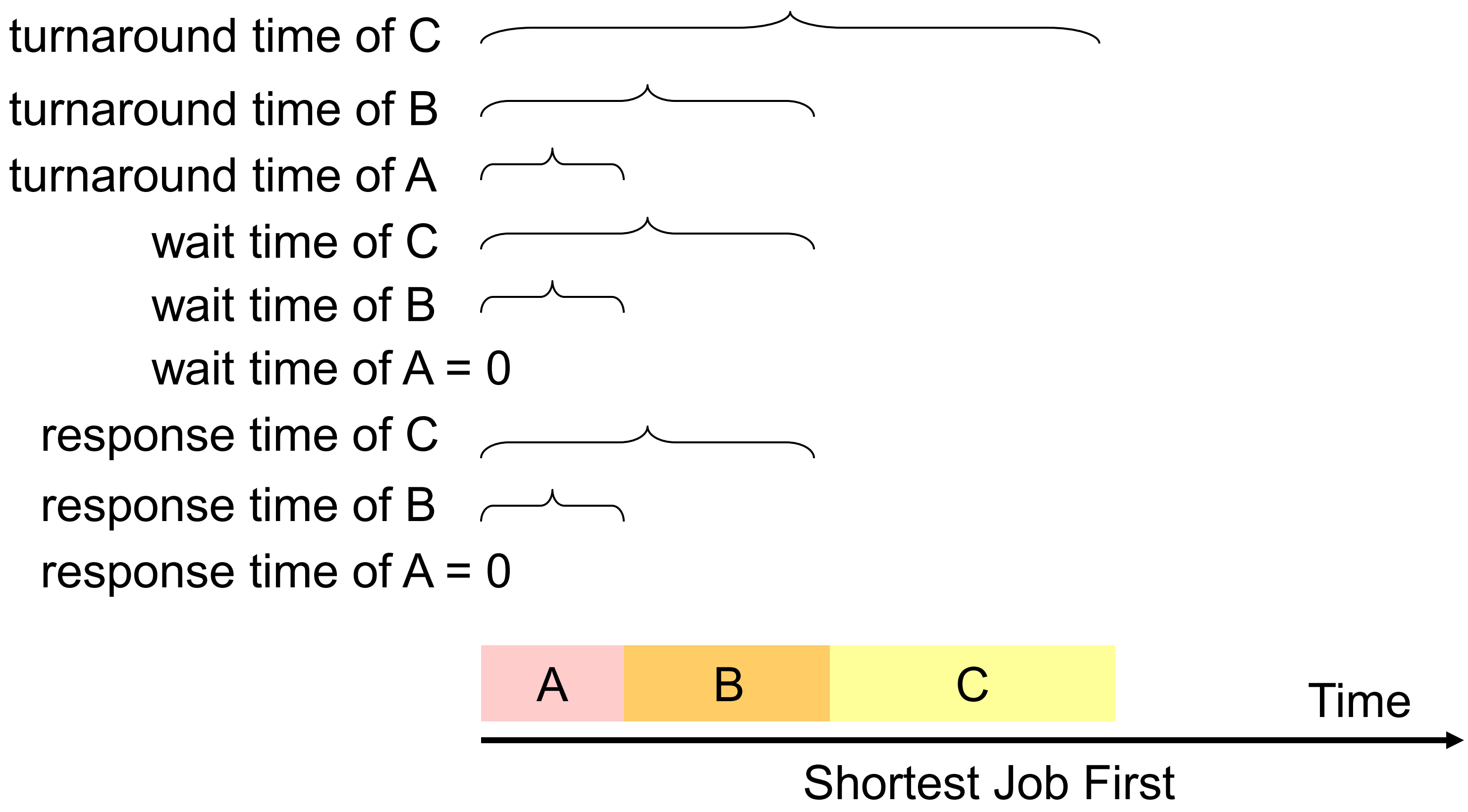
FIFO vs. Round Robin

- Round Robin
  + Shorter response time
  + Fair sharing of CPU
  - Not all jobs are preemptive
  - Not good for jobs of the same length

Shortest Job First (SJF)

- ***SJF*** runs whatever job puts the least demand on the CPU, also known as ***STCF (shortest time to completion first)***
  - \+ Provably optimal
  - \+ Great for short jobs
  - \+ Small degradation for long jobs
- Real life example: supermarket express checkouts

SJF Illustrated



Shortest Remaining Time First (SRTF)

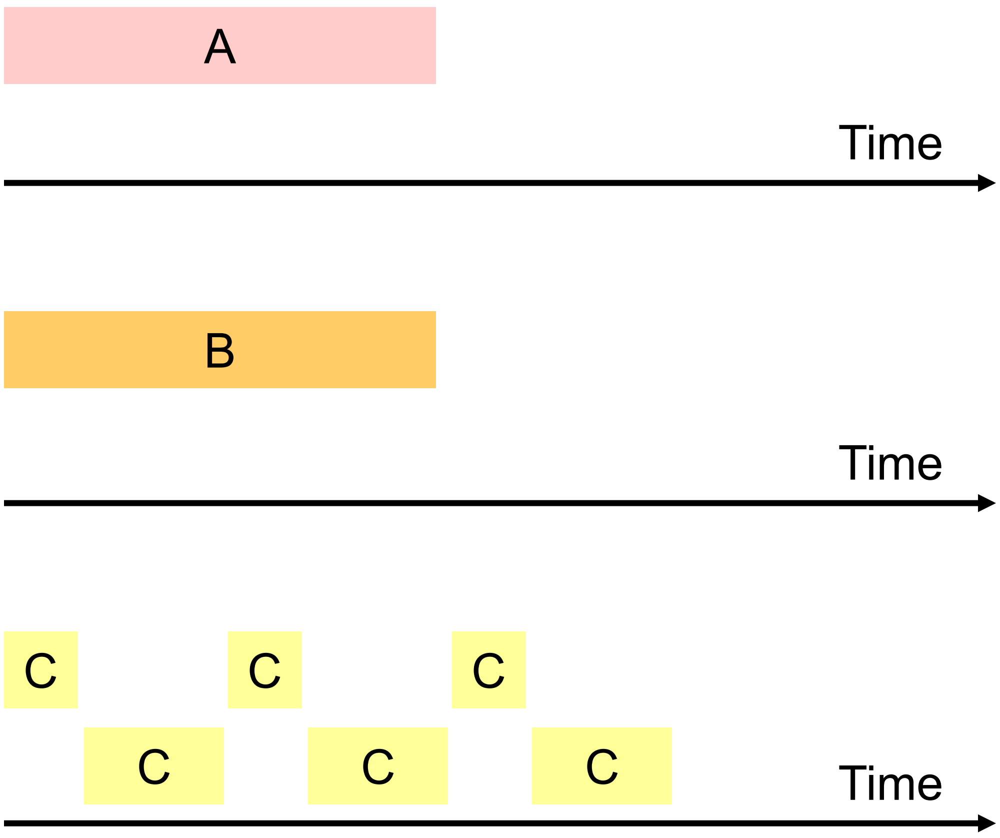
- ***SRTF***: a preemptive version of SJF
  - If a job arrives with a shorter time to completion, SRTF preempts the CPU for the new job
  - Also known as ***SRTCF (shortest remaining time to completion first)***
  - Generally used as the base case for comparisons

SJF and SRTF vs. FIFO and Round Robin

- If all jobs are the same length, SJF → FIFO
  - FIFO is the best you can do
- If jobs have varying length
  - Short jobs do not get stuck behind long jobs under SRTF

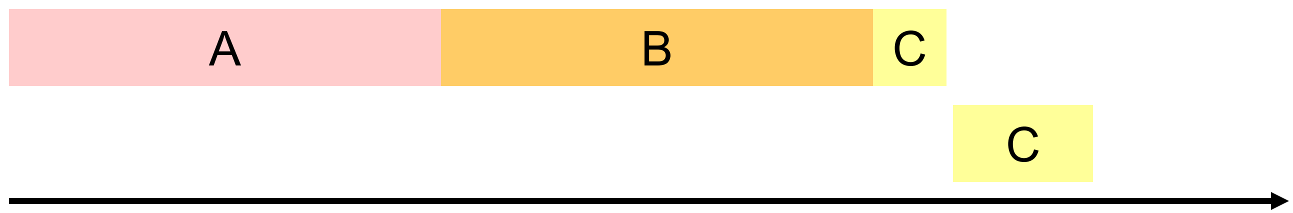
A More Complicated Scenario (Arrival Times = 0)

- Process A (6 units of CPU request)
  - 100% CPU
  - 0% I/O
- Process B (6 units of CPU request)
  - 100% CPU
  - 0% I/O
- Process C (infinite loop)
  - 33% CPU
  - 67% I/O



A More Complicated Scenario

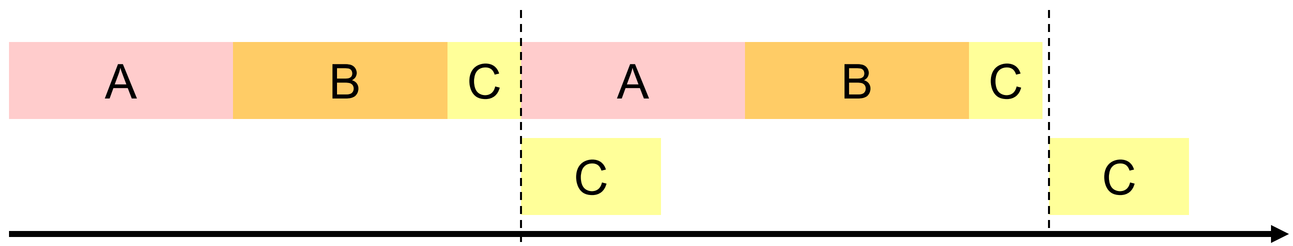
- FIFO
  - CPU
  - I/O



Poor response and wait time for process C

Time

- Round Robin with time slice = 3 units
  - CPU
  - I/O



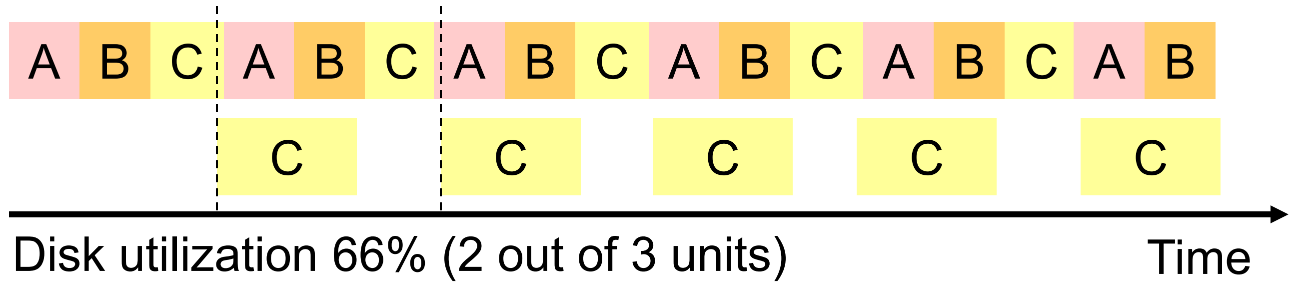
Disk utilization: 29% (2 out of 7 units)

Time

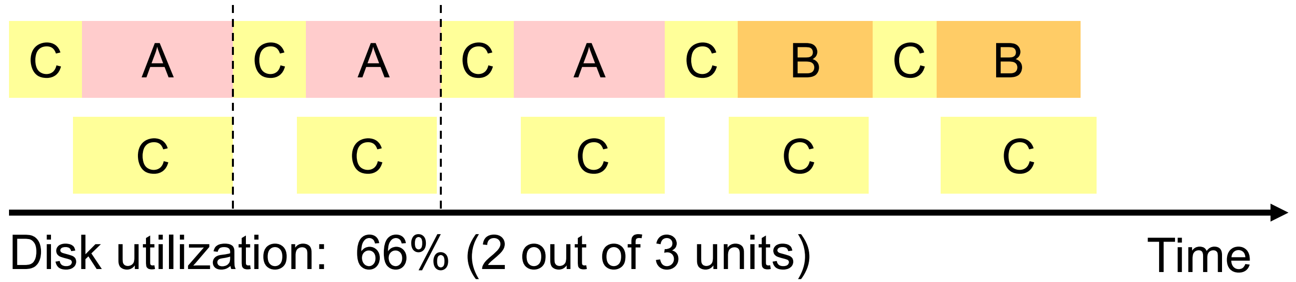
Important

A More Complicated Scenario

- Round Robin with time slice = 1 unit
  - CPU
  - I/O



- SRTCF
  - CPU
  - I/O

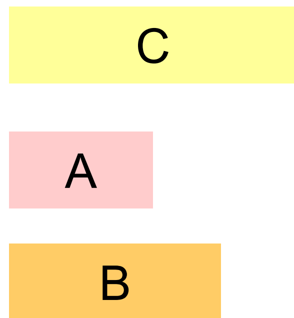


Drawbacks of Shortest Job First

- ***Starvation***: constant arrivals of short jobs can keep long ones from running
- There is no way to know the completion time of jobs (most of the time)
  - Some solutions
    - Ask the user, who may not know any better
    - If a user cheats, the job is killed

Priority Scheduling (Multilevel Queues)

- ***Priority scheduling***: The process with the highest priority runs first
- Priority 0:
- Priority 1:
- Priority 2:



- Assume that low numbers represent high priority

Priority Scheduling

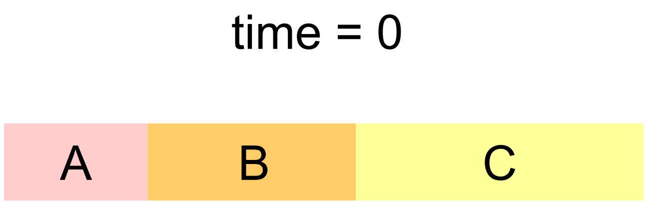
Priority Scheduling

+ Generalization of SJF
  - With SJF, higher priority is inversely proportionally to requested_CPU_time
- Starvation
  - To prevent starvation, mechanisms like aging can be used, where the priority of a process increases the longer it waits.

Multilevel Feedback Queues

- ***Multilevel feedback queues*** use multiple queues with different priorities
  - Round robin at each priority level
  - Run highest priority jobs first
  - Once those finish, run next highest priority, etc
  - Jobs start in the highest priority queue
  - If time slice expires, drop the job by one level
  - If time slice does not expire, push the job up by one level

Multilevel Feedback Queues



- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):

Important

Multilevel Feedback Queues

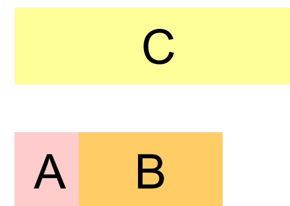
time = 1

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):

Multilevel Feedback Queues

time = 2

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):



Multilevel Feedback Queues

time = 3

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2): 

- Priority 2 (time slice = 4):

Multilevel Feedback Queues

time = 3

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):

- Priority 2 (time slice = 4):

suppose process A is blocked on an I/O

Multilevel Feedback Queues

time = 3

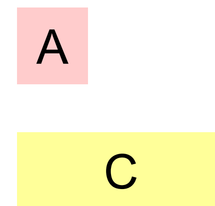
- Priority 0 (time slice = 1): A
- Priority 1 (time slice = 2): B C
- Priority 2 (time slice = 4):

suppose process A is blocked on an I/O

Multilevel Feedback Queues

time = 5

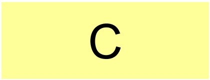
- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):



suppose process A is returned from an I/O

Multilevel Feedback Queues

time = 6

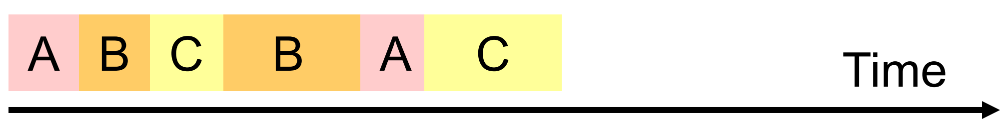
- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2): 

- Priority 2 (time slice = 4):

Multilevel Feedback Queues

time = 8

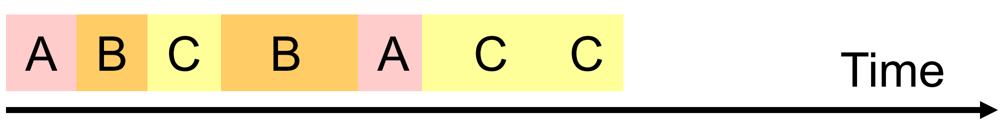
- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4): C



Multilevel Feedback Queues

time = 9

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):



Multilevel Feedback Queues

- Approximates SRTF
  - A CPU-bound job drops like a rock
  - I/O-bound jobs stay near the top
  - Still unfair for long running jobs
  - Counter-measure: ***Aging***
    - Increase the priority of long running jobs if they are not serviced for a period of time
    - Tricky to tune aging

Lottery Scheduling

- ***Lottery scheduling*** is an adaptive scheduling approach to address the fairness problem
  - Each process owns some tickets
  - On each time slice, a ticket is randomly picked
  - On average, the allocated CPU time is proportional to the number of tickets given to each job

Lottery Scheduling

- To approximate SJF, short jobs get more tickets
- To avoid starvation, each job gets at least one ticket

Lottery Scheduling Example

- short jobs: 10 tickets each
- long jobs: 1 ticket each

# short jobs/# long jobs	% of CPU for each short job	% of CPU for each long job

Important

Pros and Cons of Lottery Scheduling

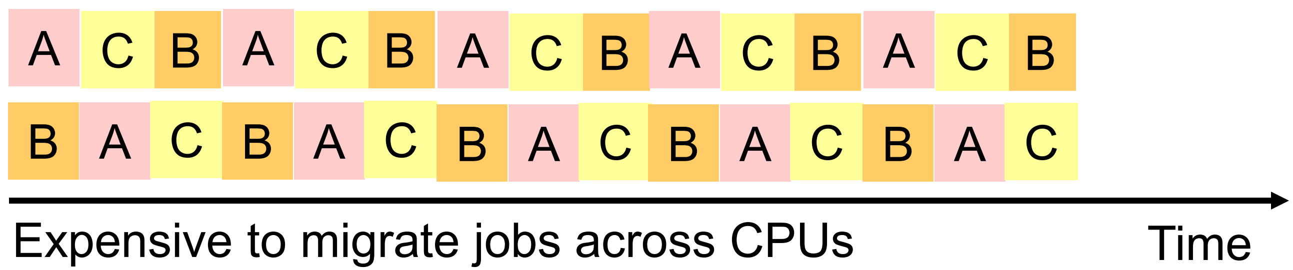
+ Good for coordinating computers with different computing power

+ Good for controlling the schedules for child processes

- Not as good for real-time systems

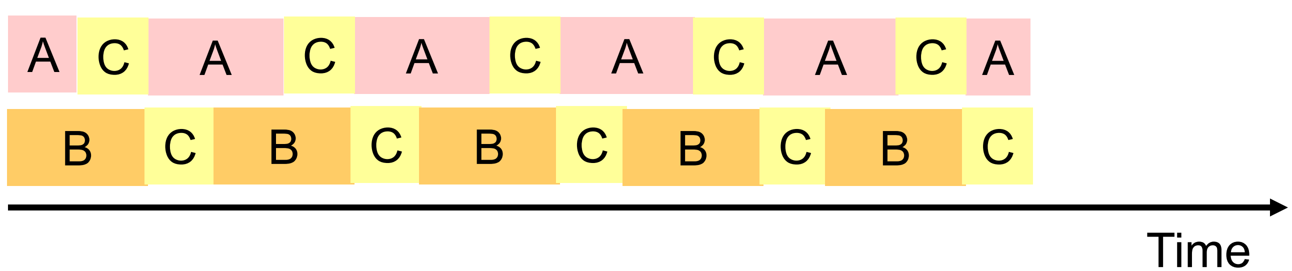
Multicore Scheduling

- Single-queue multiprocessor scheduling (SQMS)
  - CPU1
  - CPU2



Expensive to migrate jobs across CPUs
(Poor ***CPU affinity***)

- Another SQMS
  - CPU1
  - CPU2

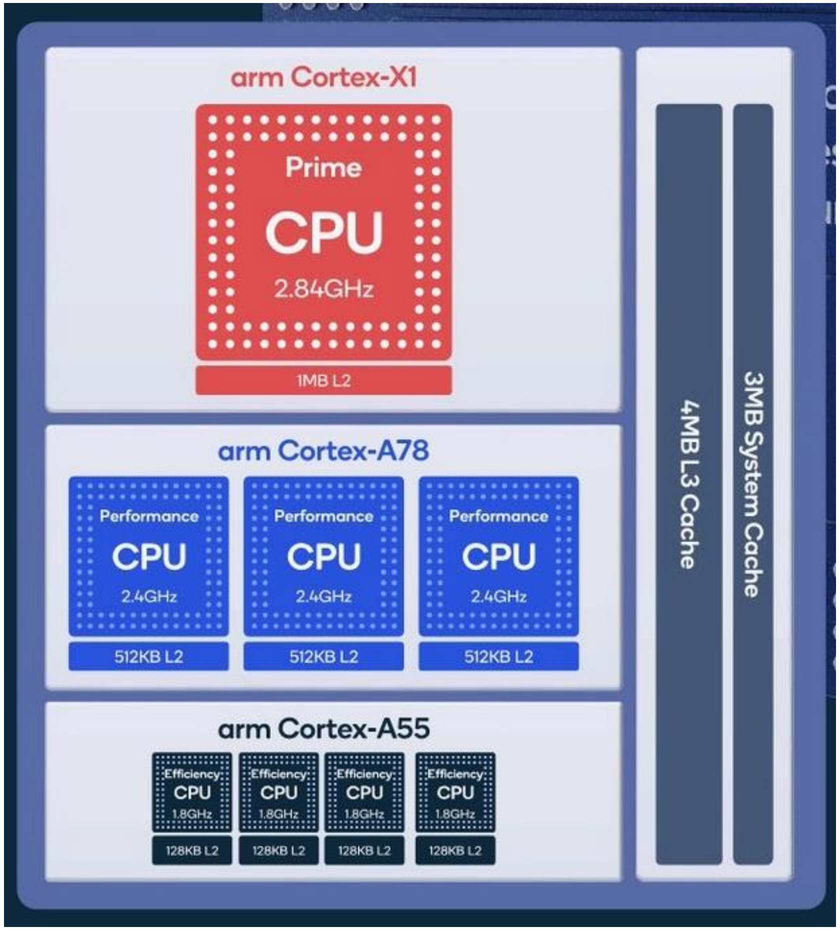


More Schedulers

- Multi-queue scheduling
- O(1) scheduler
- Completely Fair Scheduler (CFS)

Real World

- Big.LITTLE
  - Snapdragon 888
- Others
  - The physical distance between CPUs on the circuit board
  - Power
  - …



Takeaways

- OS is a state machine.
- Process, Thread, Address Space
- Thread Dispatch Loop
- Amdahl's Law
- CPU Scheduling