CS 3502
Operating Systems

Scheduling

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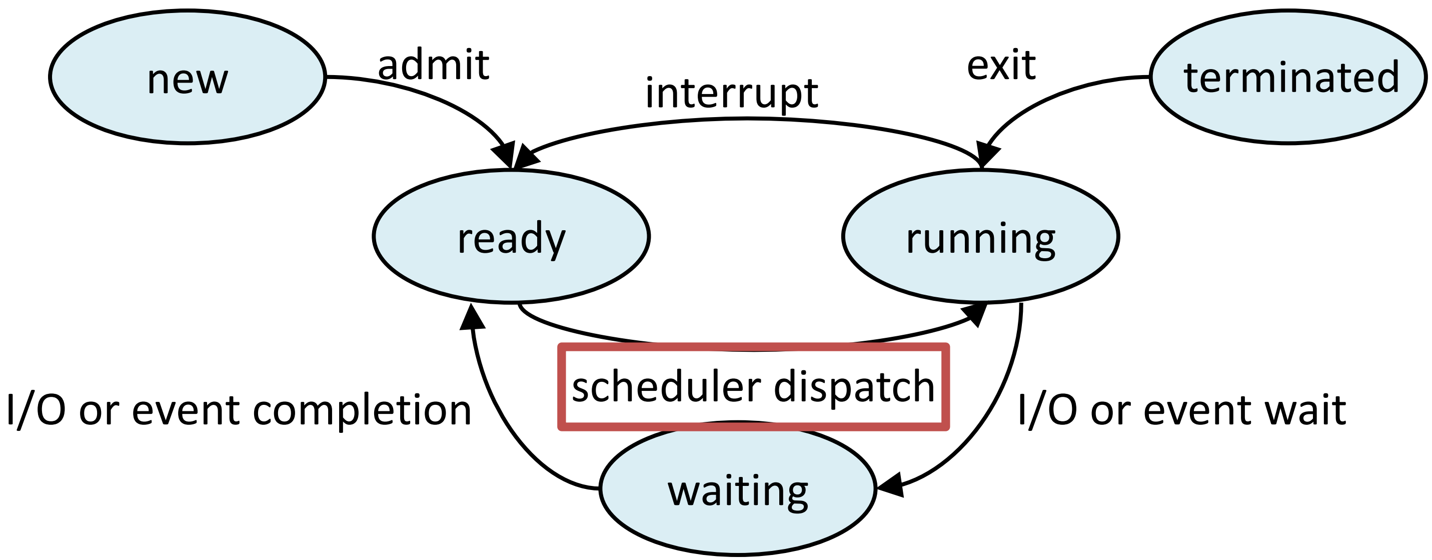
https://kevinsuo.github.io/

Outline

- Introduction to CPU scheduling
  - What is CPU scheduling
  - Why we need CPU scheduling
  - When scheduling happens
- Scheduling policies
  - FCFS, SJF, RR, Priority
  - Scheduling on multiple CPUs

What is CPU scheduling?

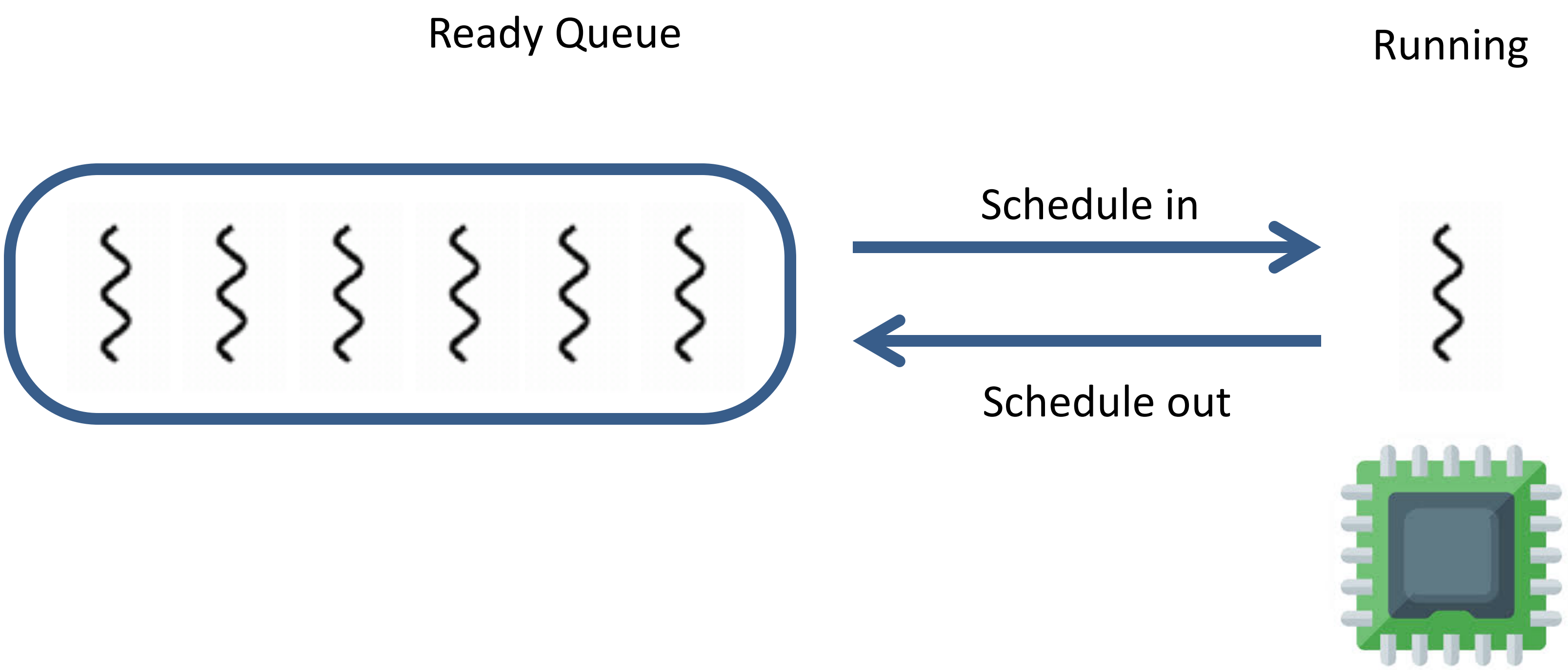
- The five-state process model



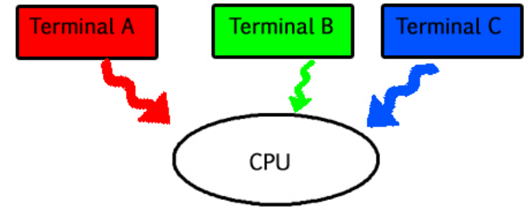
CPU scheduling

Selects from among the processes/threads that are ready to execute, and allocates the CPU to it

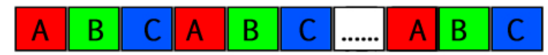
What is CPU scheduling?

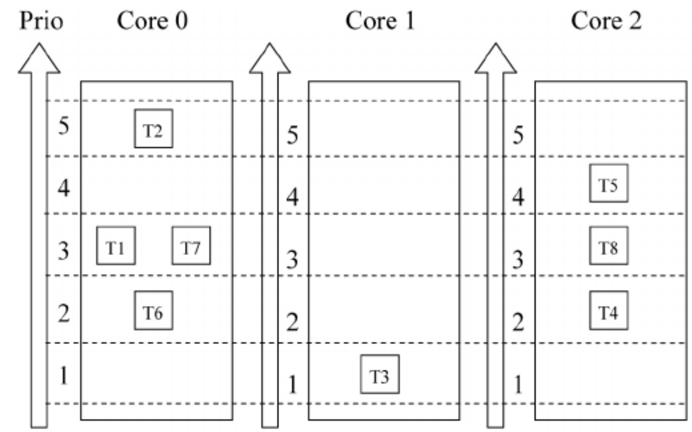


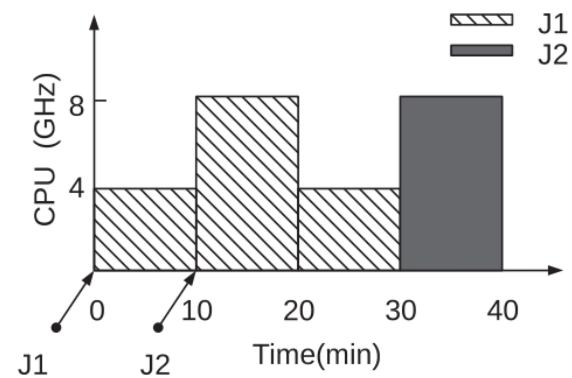
Why CPU scheduling?



- In support of multiprogramming
  - uniprocessor systems
    - Time-sharing processor
  - multiprocessor systems
    - Efficiently distributing tasks
  - Real-time systems
    - Reliably guaranteeing deadlines





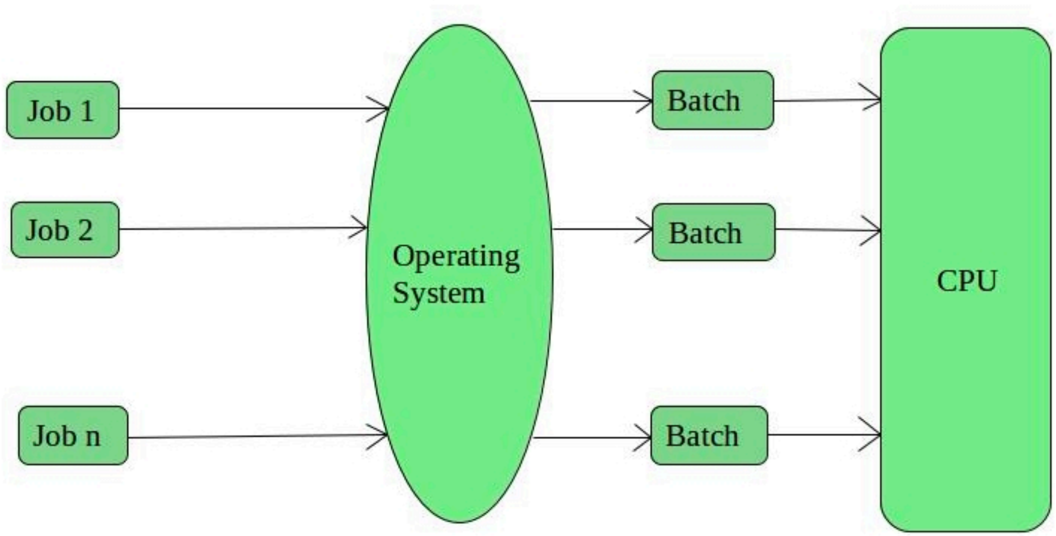


Why CPU scheduling? – Different Goals

- All systems
  - Fairness - giving each process a fair share of the CPU
  - Policy enforcement - seeing that stated policy is carried out
  - Balance - keeping all parts of the system busy

Why CPU scheduling? – Different Goals

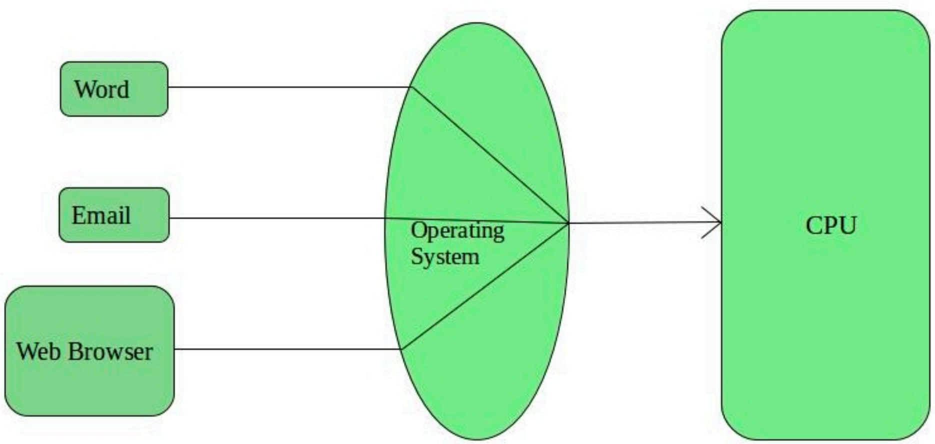
- Batch systems
  - Throughput - maximize jobs per hour
  - Turnaround time - minimize time between submission and termination
  - CPU utilization - keep the CPU busy all the time



National lab:
Scientific research
Energy, nuclear, climate, …

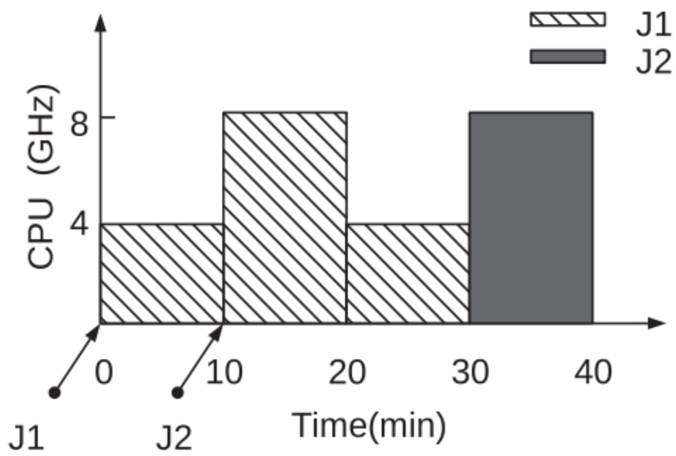
Why CPU scheduling? – Different Goals

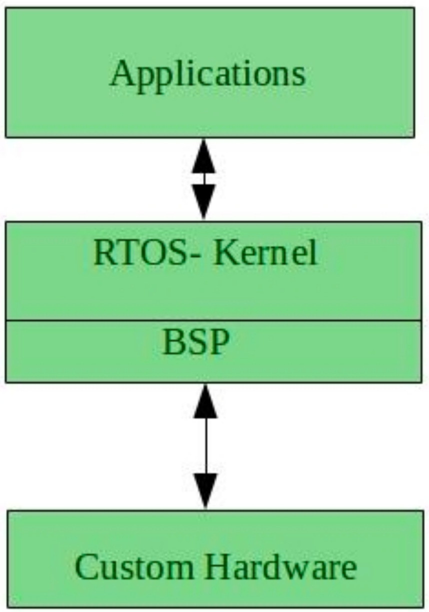
- Interactive systems
  - Response time - respond to requests quickly
  - Proportionality - meet users' expectations



Why CPU scheduling? – Different Goals

- Real-time systems
  - Meeting deadlines - avoid losing data
  - Predictability - avoid quality degradation in multimedia systems





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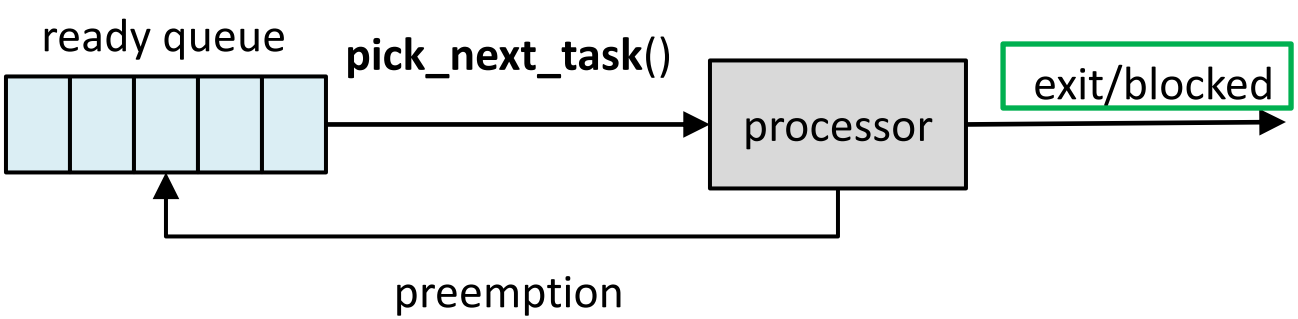
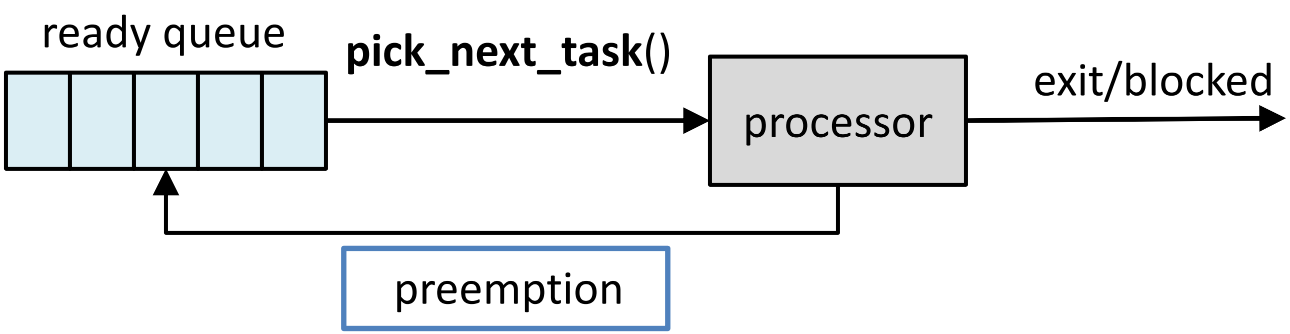
When scheduling happens?

- Non-preemptive
  - Scheduling only when current process terminates or gives up control



When scheduling happens?

- Preemptive
  - Processes can be forced to give up control

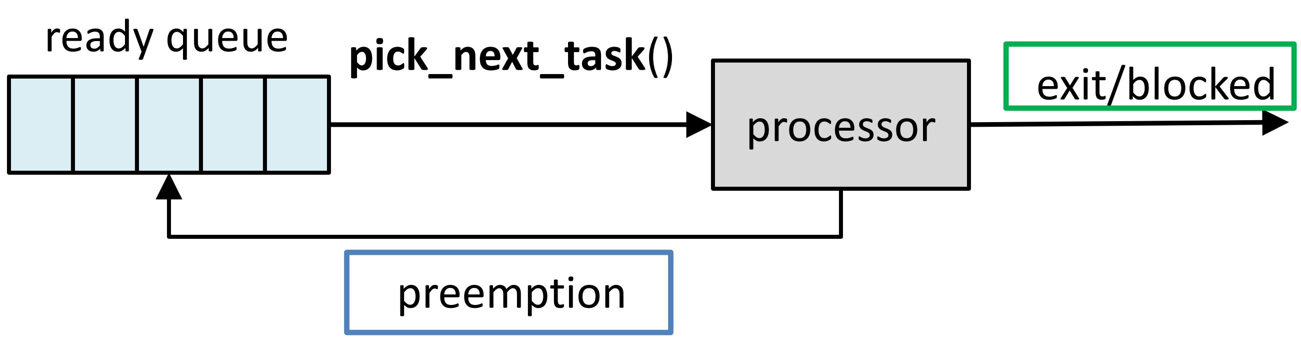


When scheduling happens?

- CPU scheduling may take place at
  - Clock interrupts
  - I/O interrupts
  - I/O completion
  - Termination

preemptive (Clock interrupts, I/O interrupts)

non-preemptive (I/O completion, Termination)



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Scheduling Policies

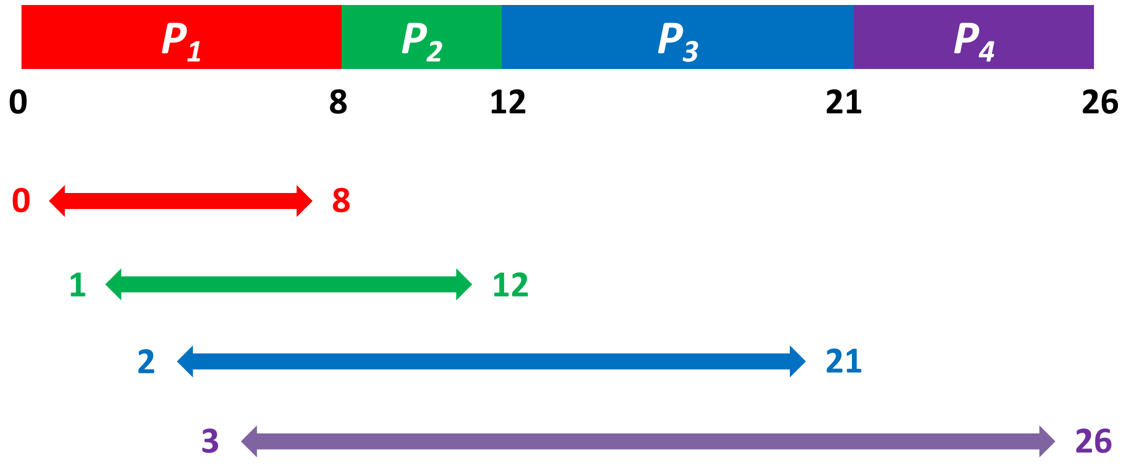
- Batch Systems
  - First-Come First-Serve (FCFS)
  - Shortest Job First
  - Shortest Remaining Time Next
- Interactive Systems
  - Round-Robin
  - Priority Scheduling
  - Multiple Queues
  - Shortest Process Next
  - Guaranteed Scheduling
  - Lottery Scheduling
- Real-time Systems
  - Rate Monotonic Scheduling
  - Earliest Deadline First Scheduling

Not exist best scheduling.
It depends on your goals.

Determine the next
ready task to run

Turnaround time = End time – Arrival time

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



Response time = Start time – Arrival time

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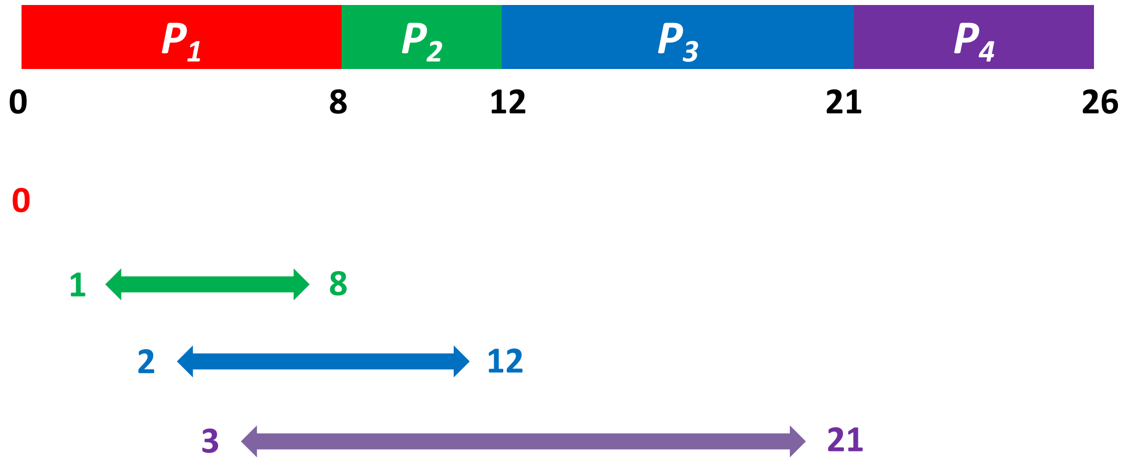

First-Come, First-Serve (FCFS)

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

- CPU schedules the task that arrived earliest, non-preemptive

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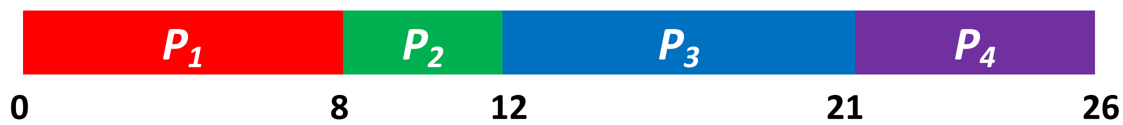

Average turnaround time = ?

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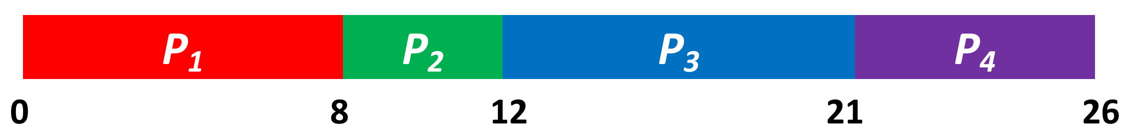

Average turnaround time = ((8-0)+(12-1)+(21-2)+(26-3)) / 4 = 15.25

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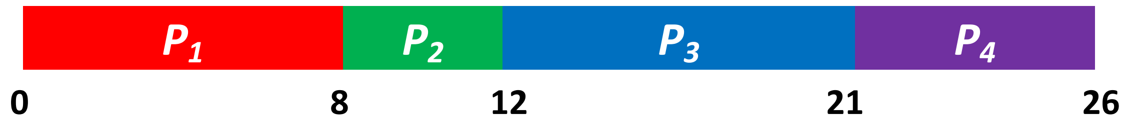

Average response time = (0+(8-1)+(12-2)+(21-3)) /4 = 8.75

Shortest Job First (SJF)

- CPU schedules the task with the shortest remaining time

Process	Arrival Time	Burst Time
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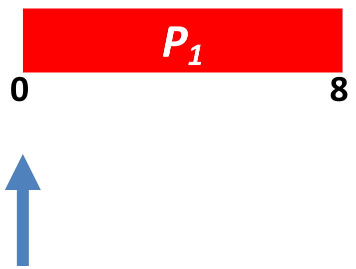
non-preemptive



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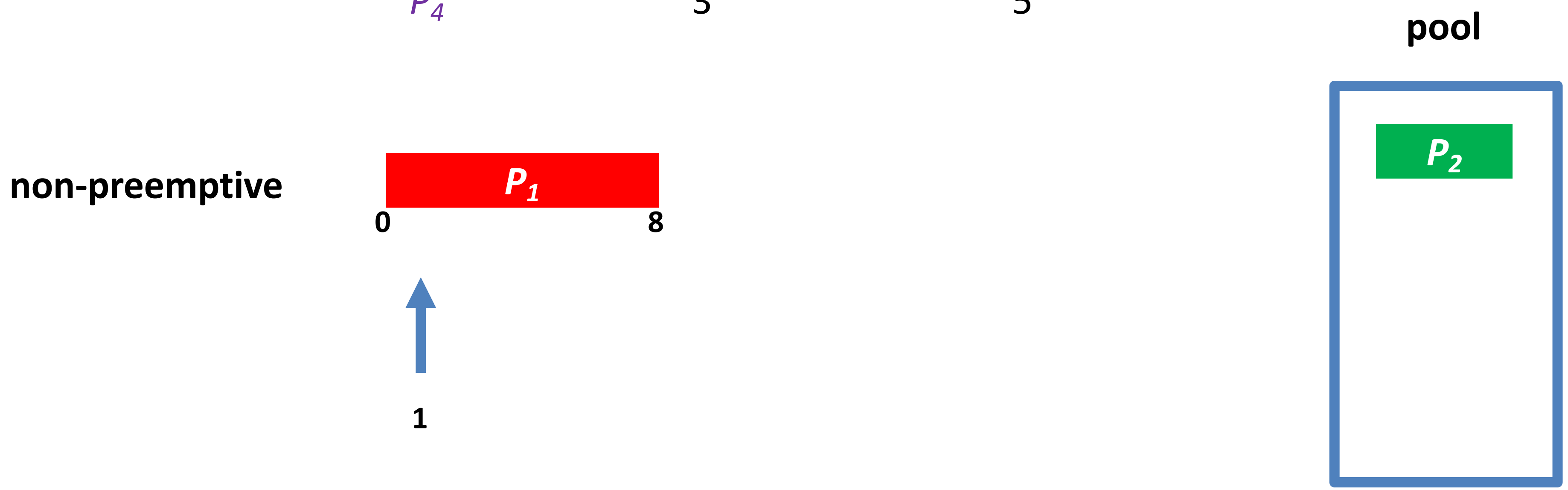

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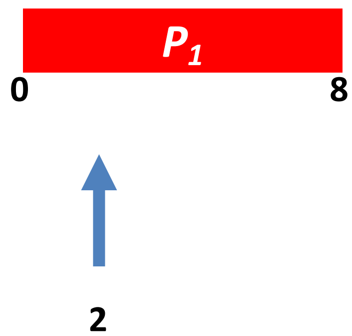
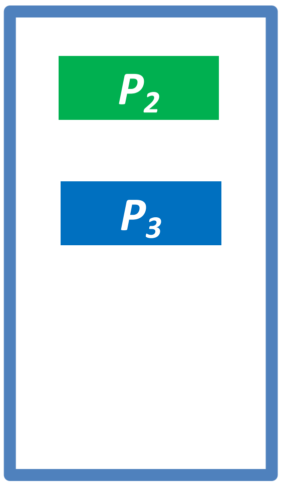


pool



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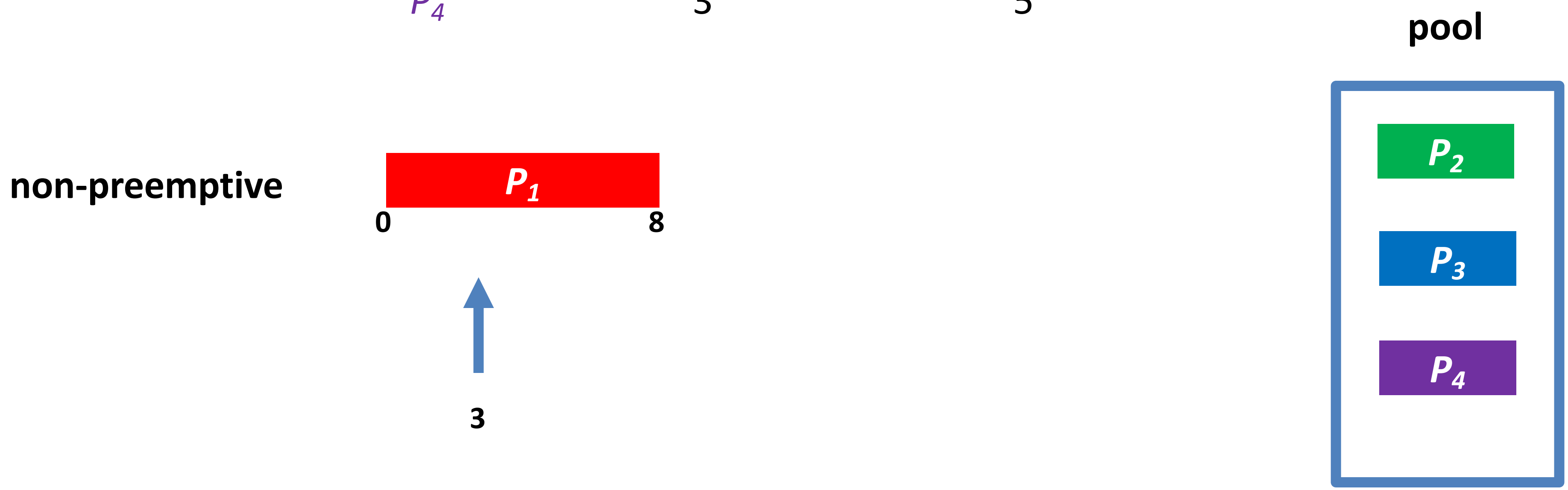

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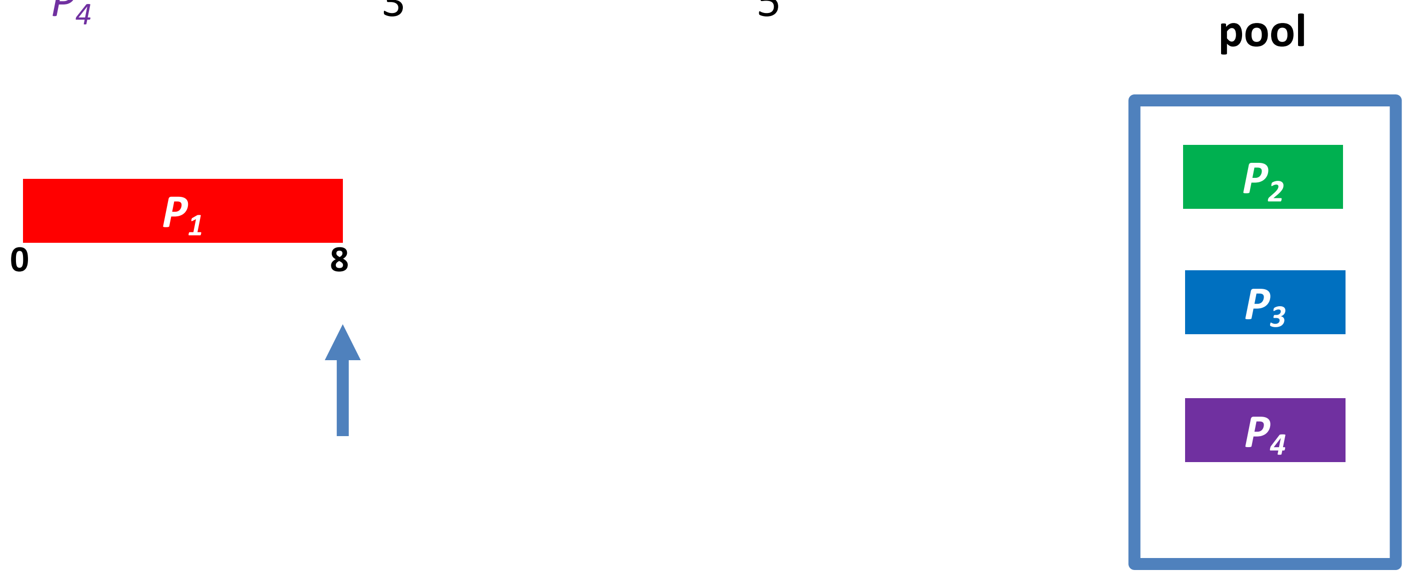

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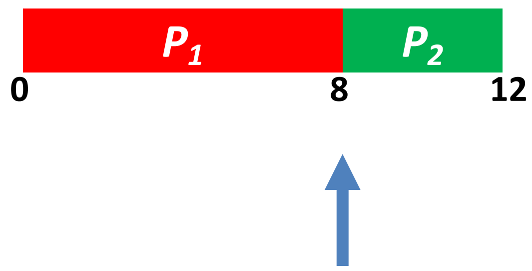

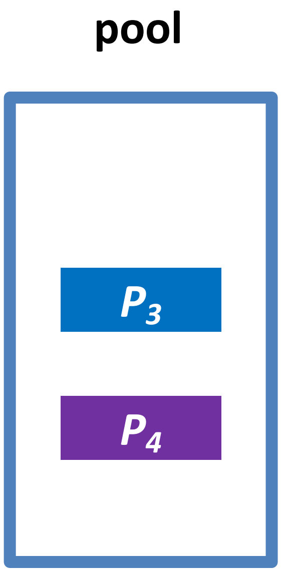

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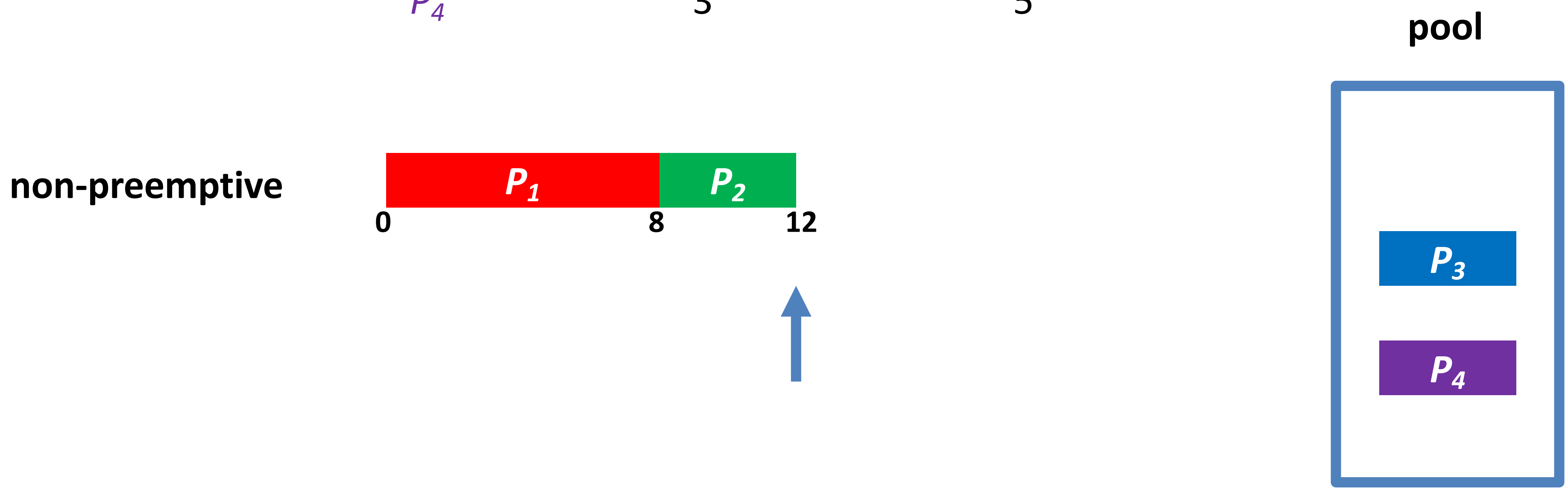

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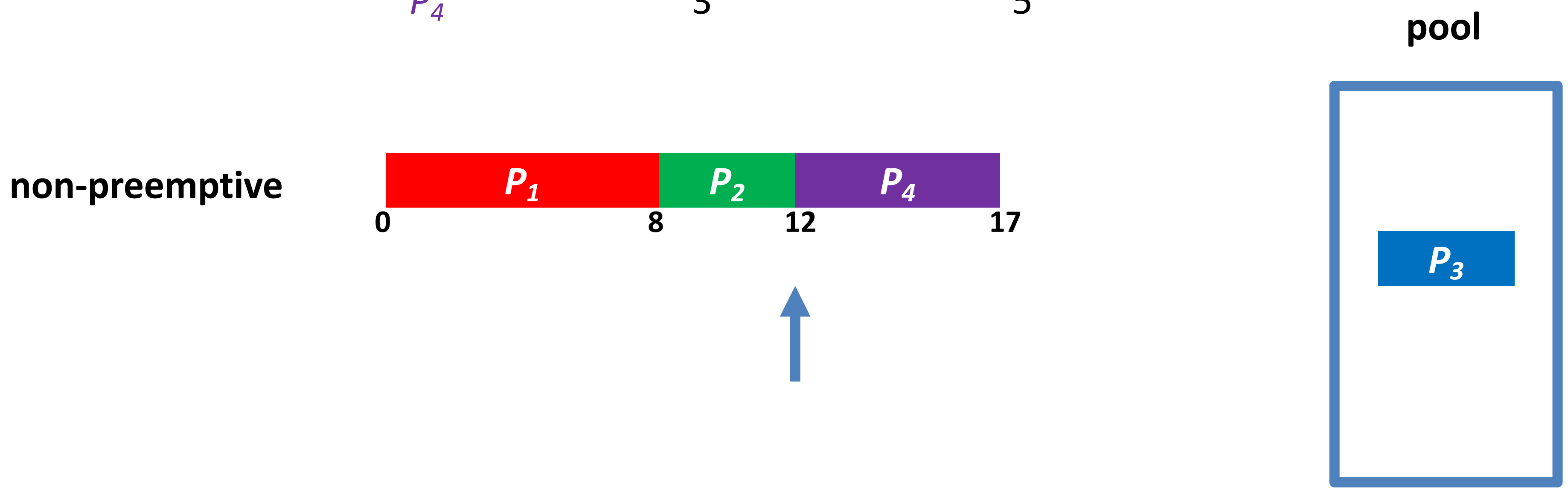

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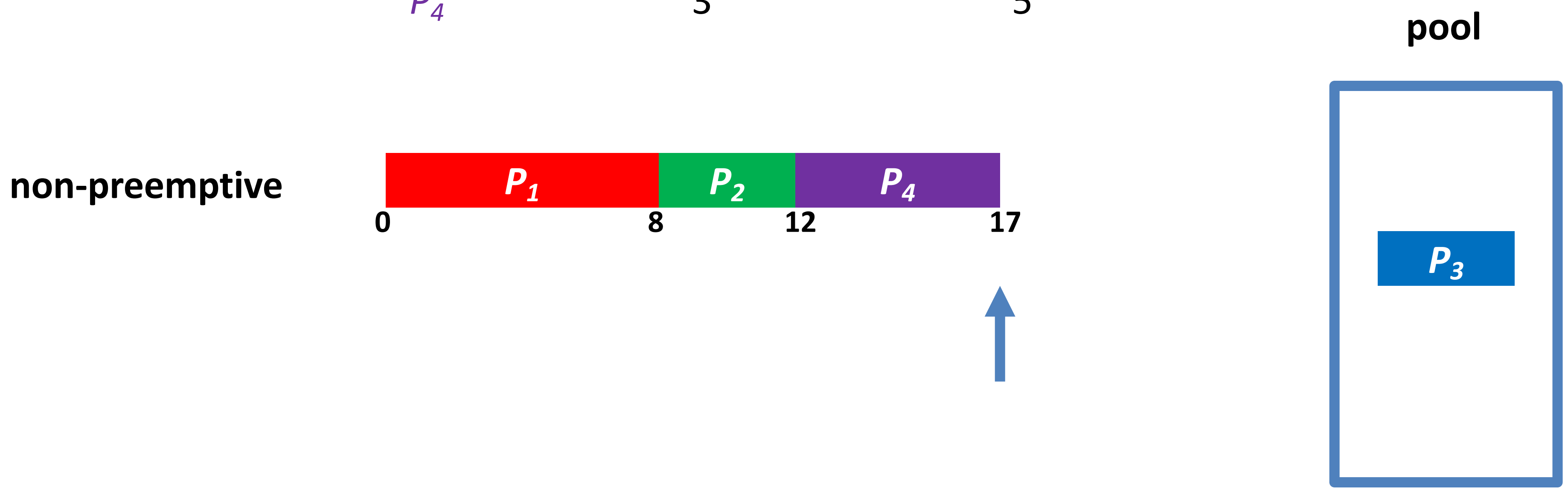

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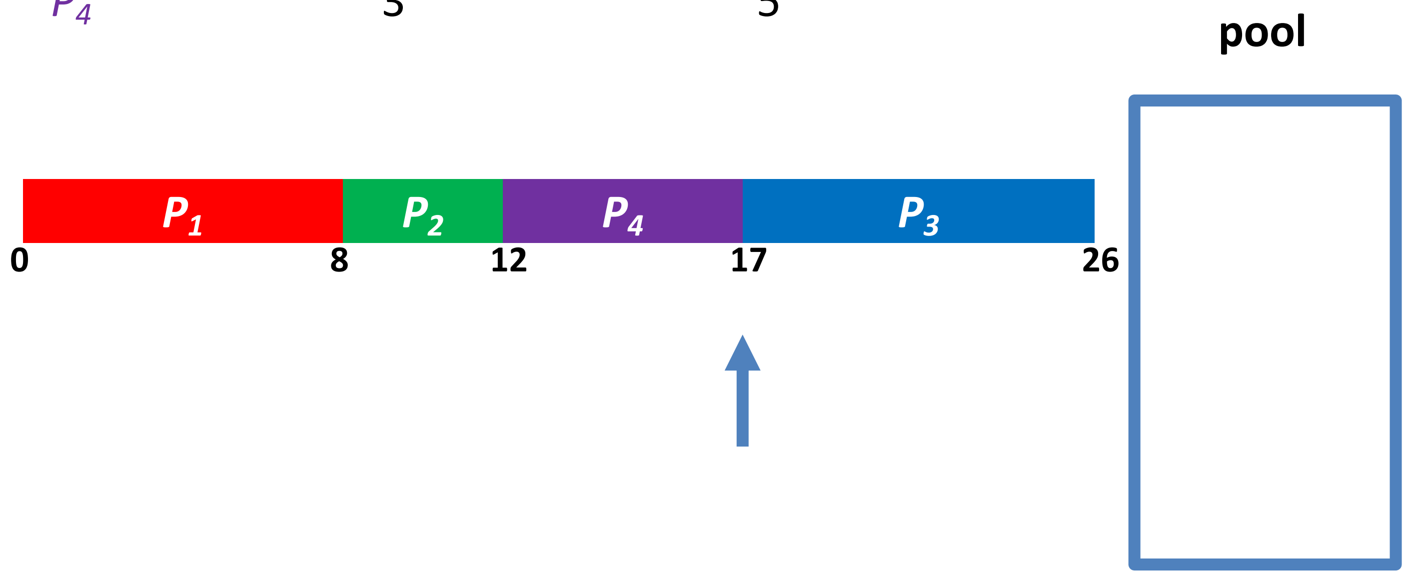

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Average turnaround time = ?

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non-preemptive

Average turnaround time = ((8-0)+(12-1)+(26-2)+(17-3)) / 4 = 14.25

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non-preemptive

Average response time = ?

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P_4	3	5

non-preemptive

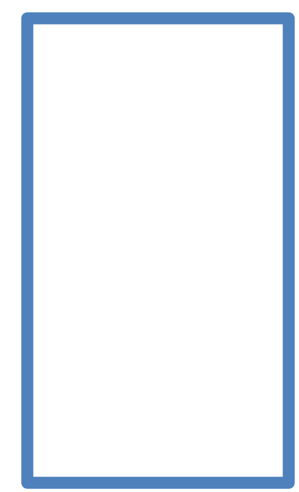
Average response time = (0+(8-1)+(17-2)+(12-3)) /4 = 7.75

Shortest Job First (SJF) with preemption

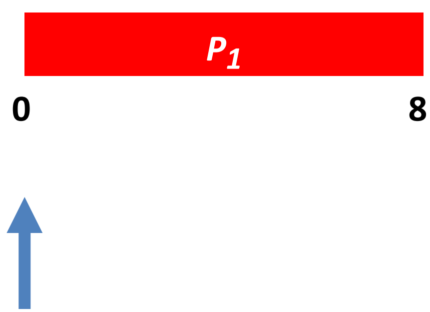
- CPU schedules the task with the shortest remaining time

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



preemptive



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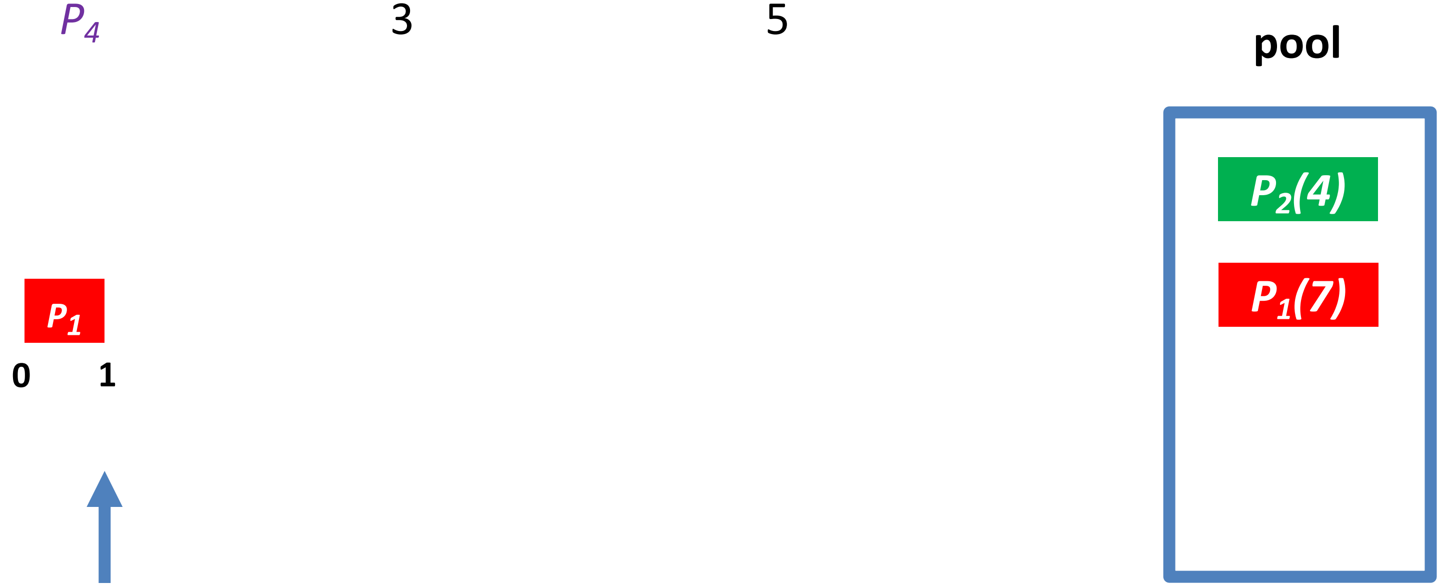

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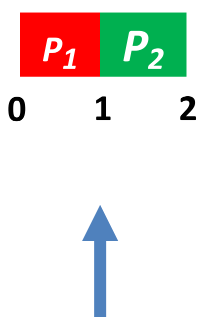

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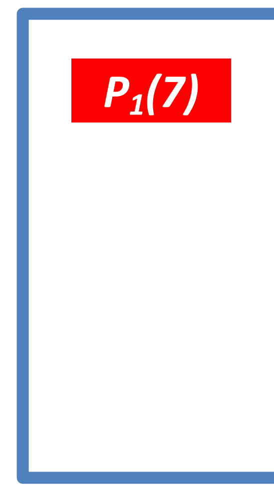

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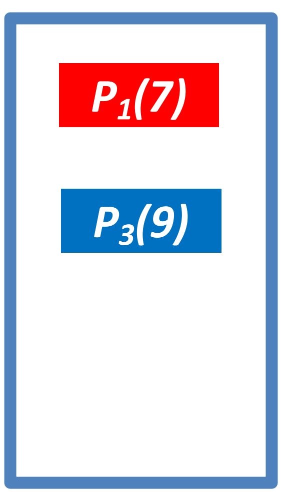

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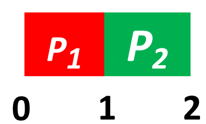

P2 remain =3

Shortest Job First (SJF) with preemption

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P_2	1	4
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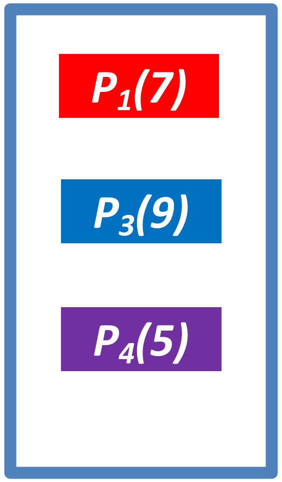
pool



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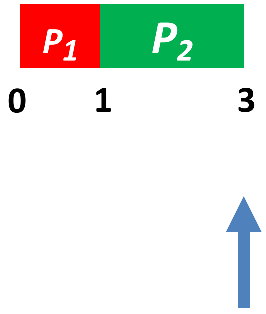

P2 remain =2

Shortest Job First (SJF) with preemption

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P_1	0	8
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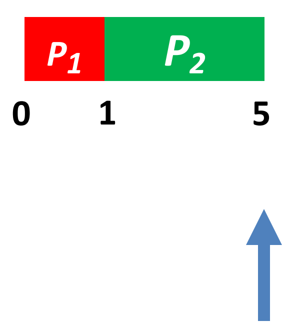
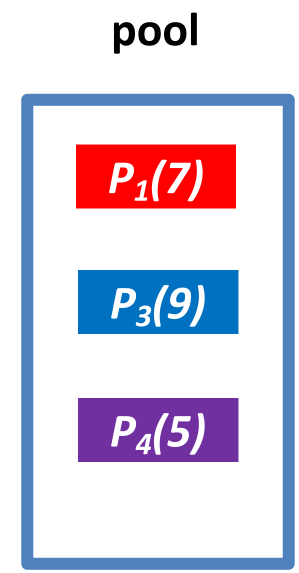
preemptive





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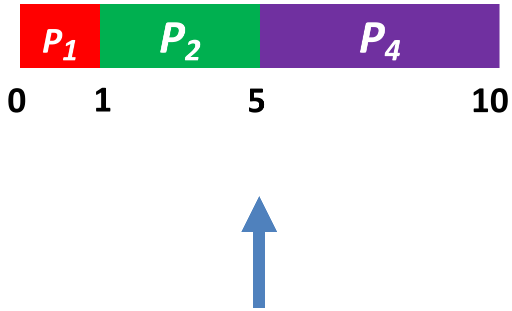

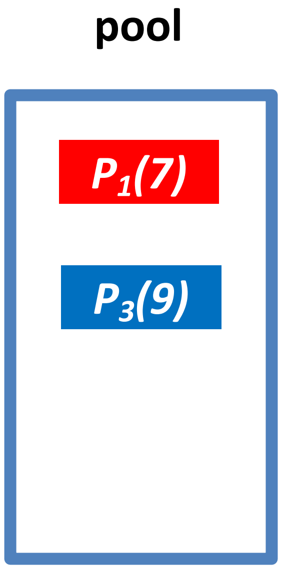

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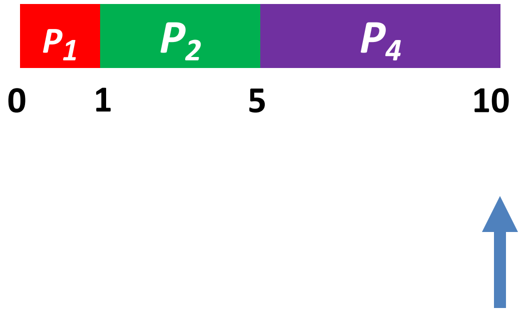
preemptive



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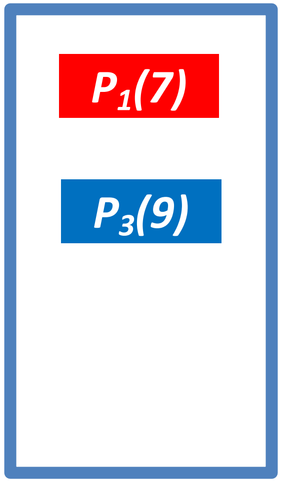

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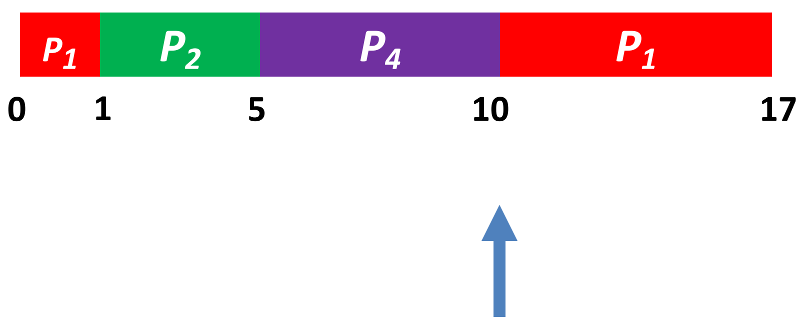
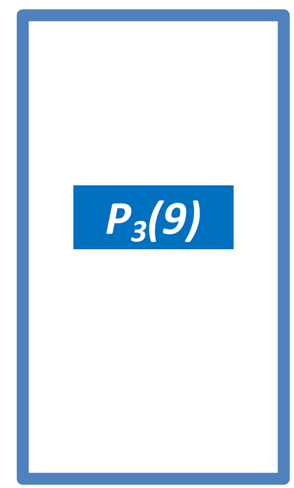


pool

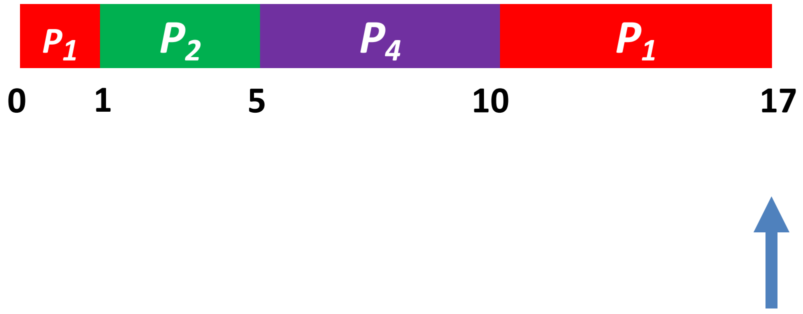


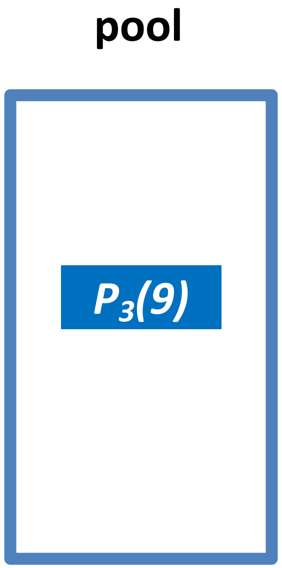
Shortest Job First (SJF) with preemption

- CPU schedules the task with the shortest remaining time

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

preemptive





Shortest Job First (SJF) with preemption

- CPU schedules the task with the shortest remaining time

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

preemptive

Average turnaround time = ?

Shortest Job First (SJF) with preemption

- CPU schedules the task with the shortest remaining time

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

preemptive

Average turnaround time = ((17-0)+(5-1)+(10-3)+(26-2)) / 4 = 13

Shortest Job First (SJF) with preemption

- CPU schedules the task with the shortest remaining time

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

preemptive

Average response time = ?

Shortest Job First (SJF) with preemption

- CPU schedules the task with the shortest remaining time

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

preemptive

P_1	P_2	P_4	P_1	P_3
0–1	1–5	5–10	10–17	17–26

Average response time = (0+(1-1)+(5-3)+(17-2)) /4 = 4.25

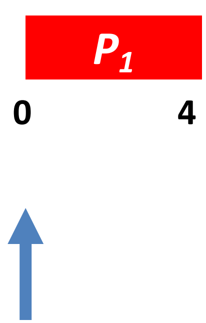
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

pool

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

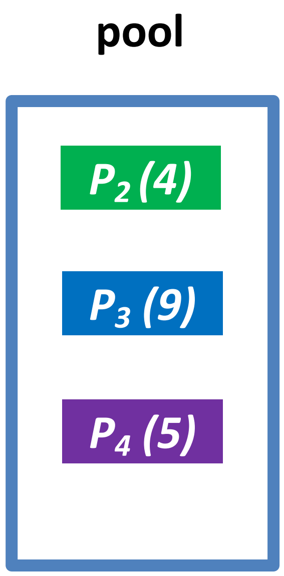
***q*=4**

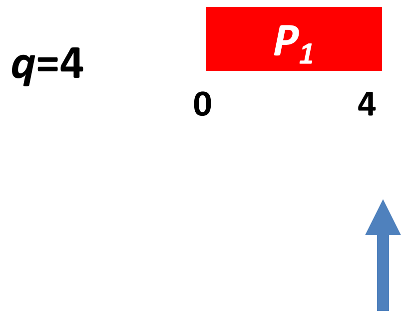


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



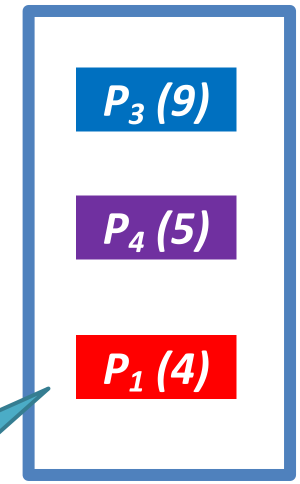


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

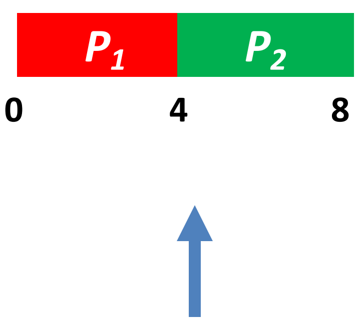
Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



P1 is put at the end of queue after scheduled out

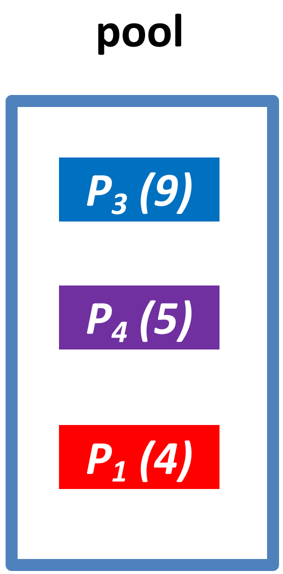
***q*=4**



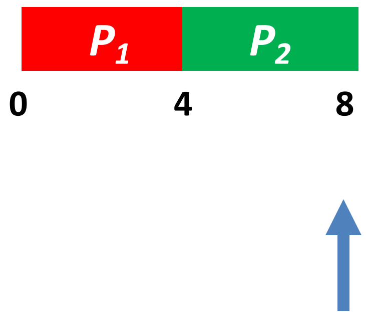
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



***q*=4**

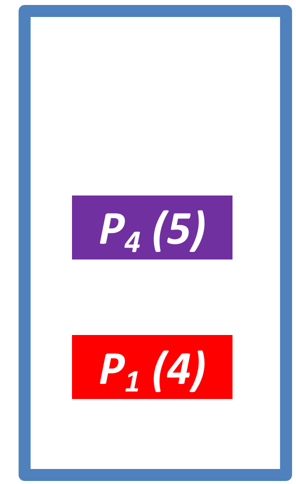


Round Robin (RR)

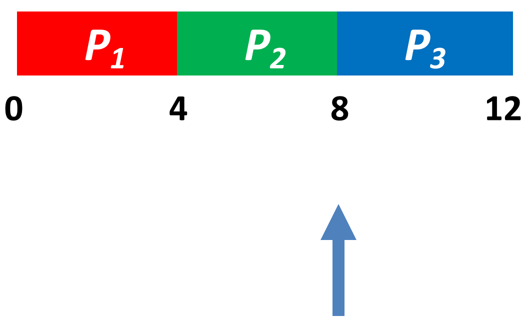
- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



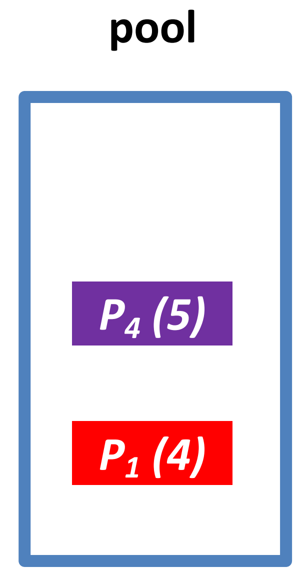
q=4

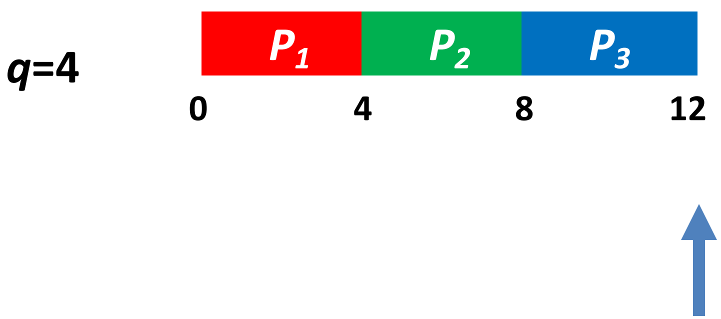


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



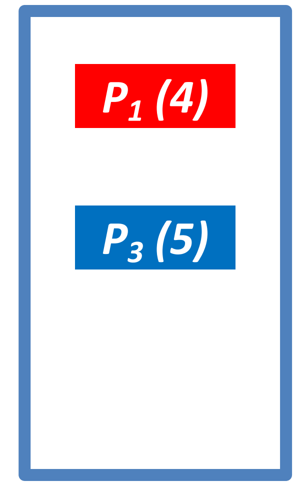


Round Robin (RR)

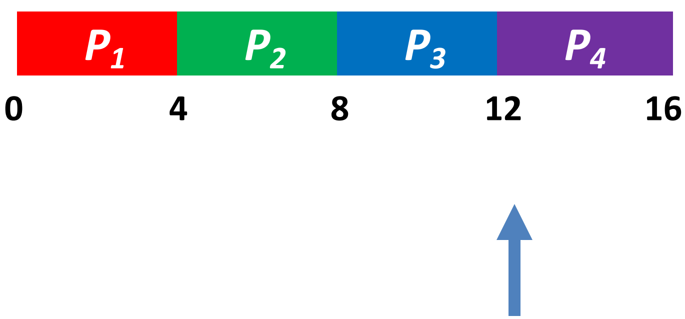
- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



q=4

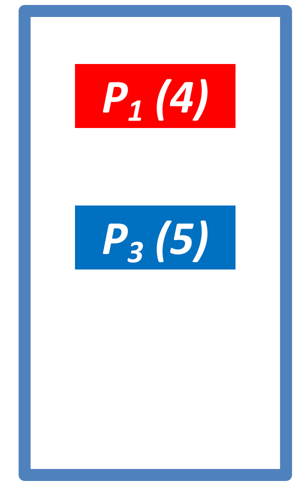


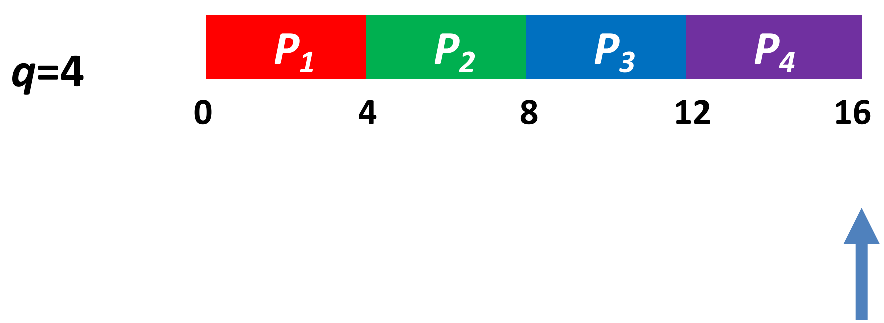
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



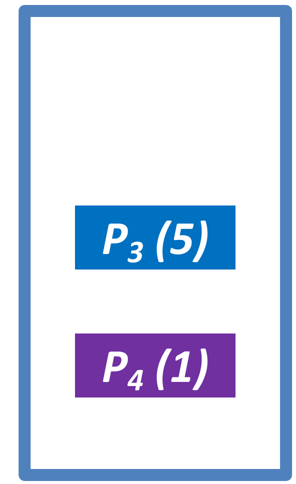


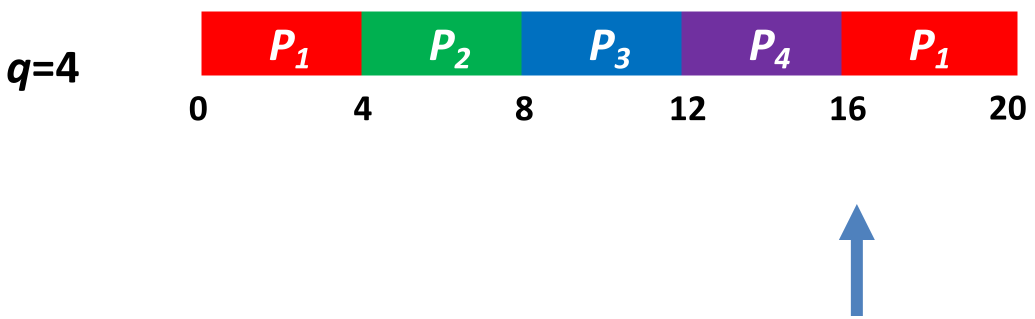
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool

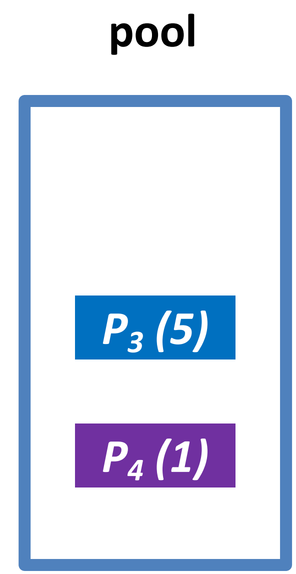


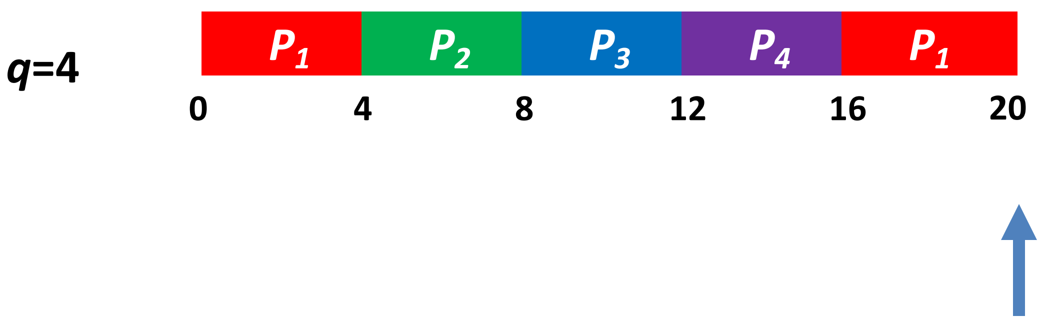


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

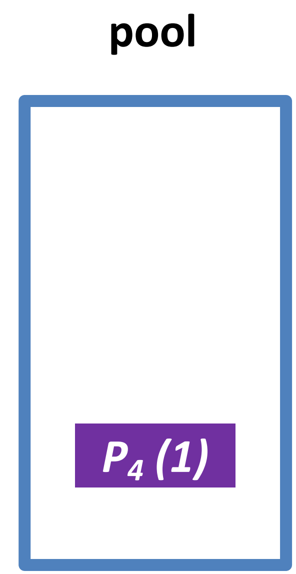


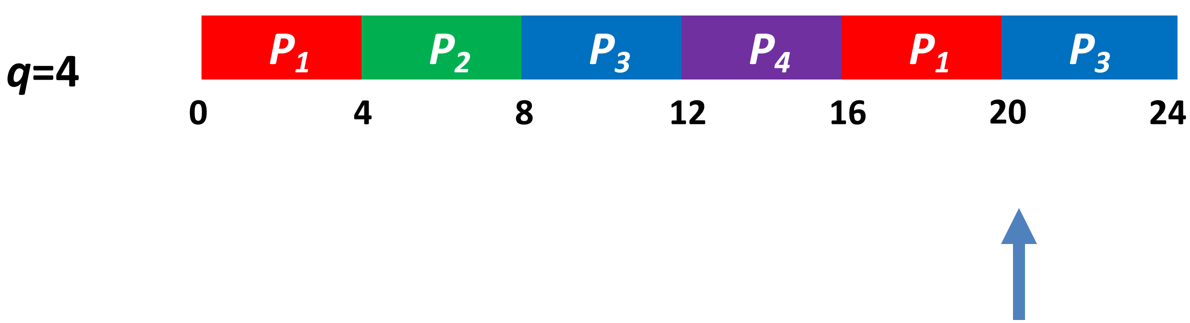


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

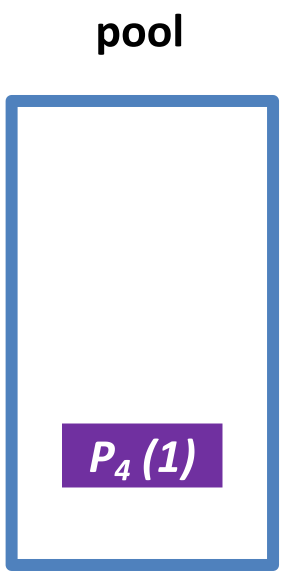


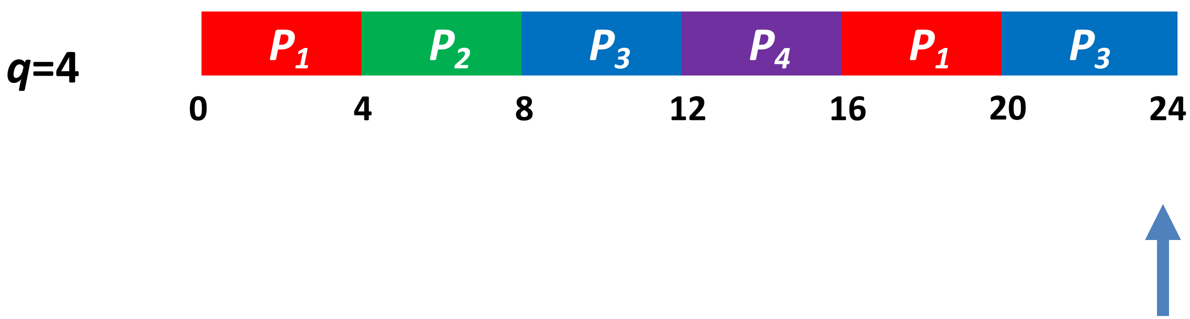


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



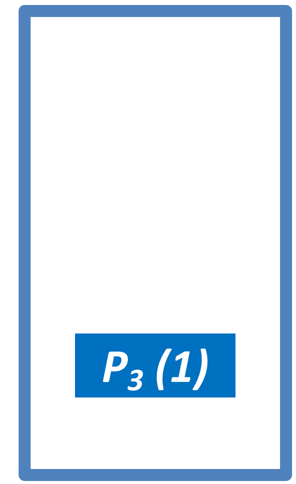


Round Robin (RR)

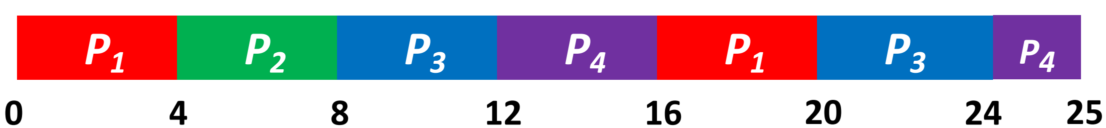
- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



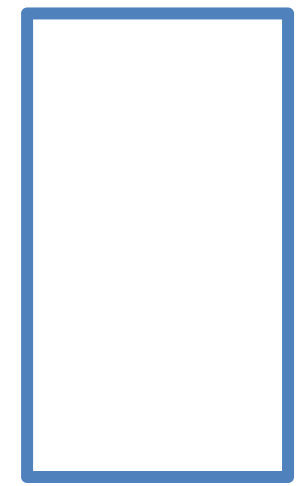
***q*=4**



Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

pool



Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

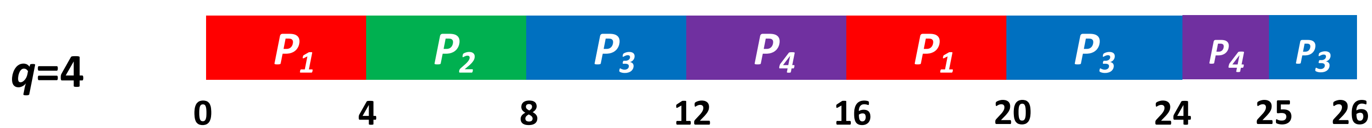
***q*=4**

Round Robin (RR)

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



Average turnaround time = ?

Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

***q*=4**

Average turnaround time = ((20-0)+(8-1)+(26-2)+(25-3)) / 4 = 18.25

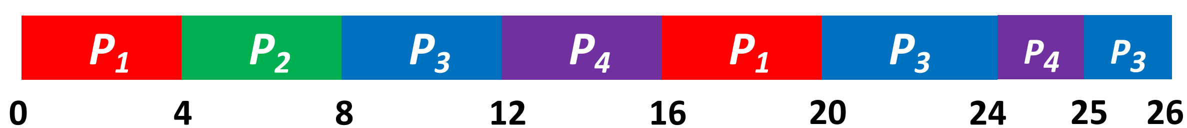
Round Robin (RR)

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

***q*=4**



Average response time = ?

Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

q=4

Average response time = (0+(4-1)+(8-2)+(12-3)) /4 = 4.5

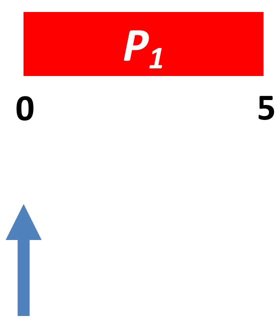
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

pool

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

***q*=5**

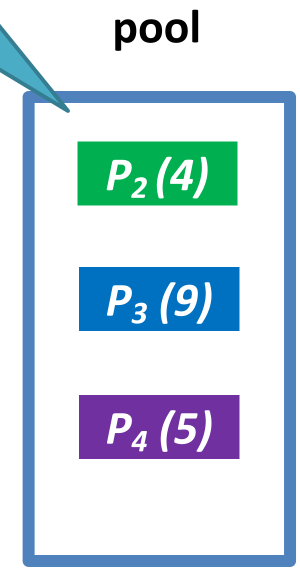


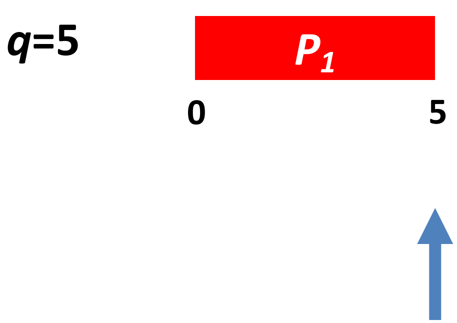
Round Robin (RR)

Select the task at the beginning

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

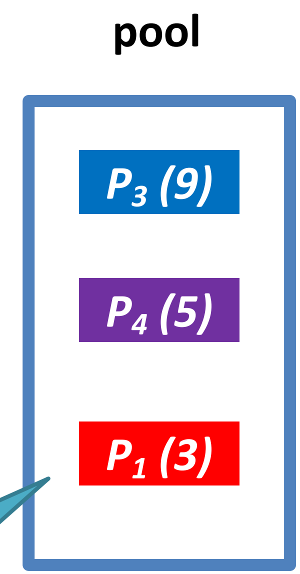


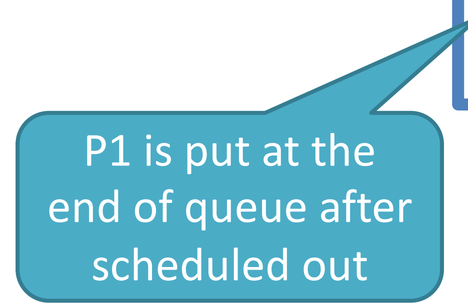


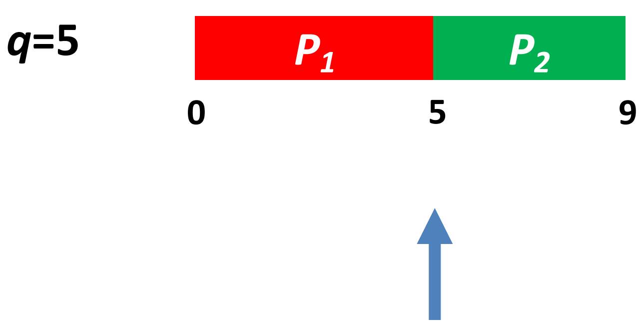
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5





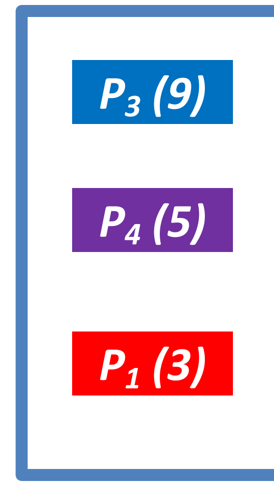


Round Robin (RR)

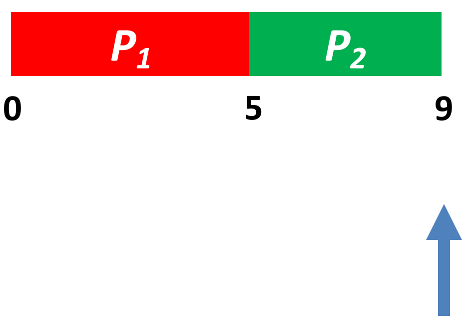
- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



***q*=5**

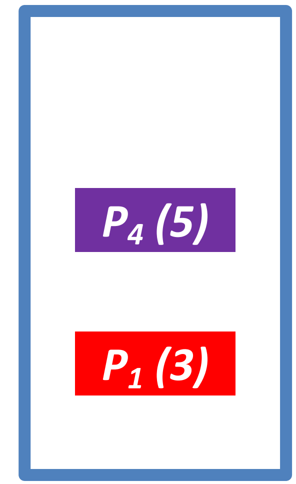


Round Robin (RR)

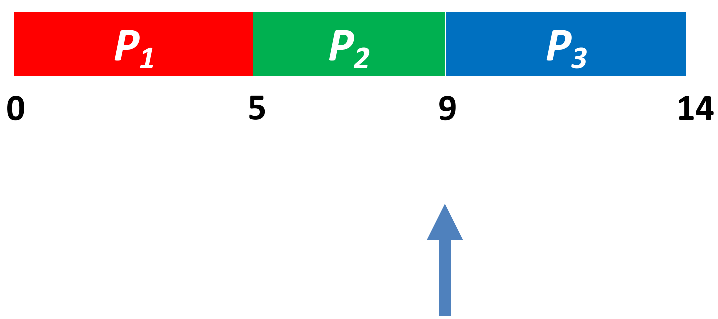
- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool



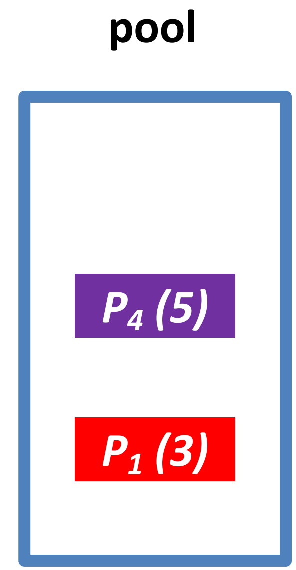
q=5

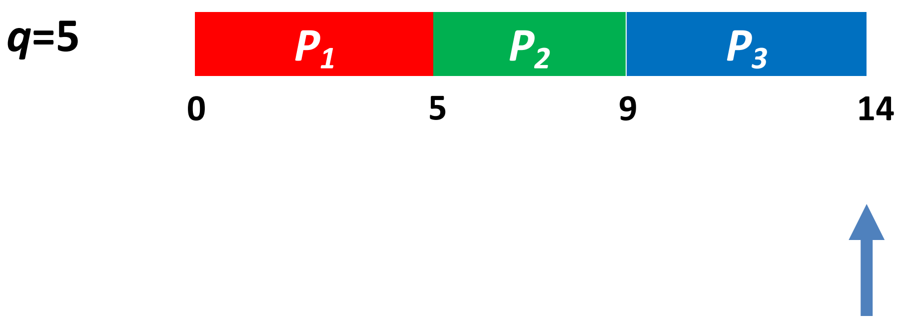


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

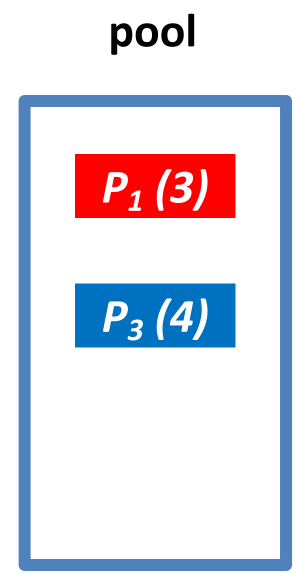


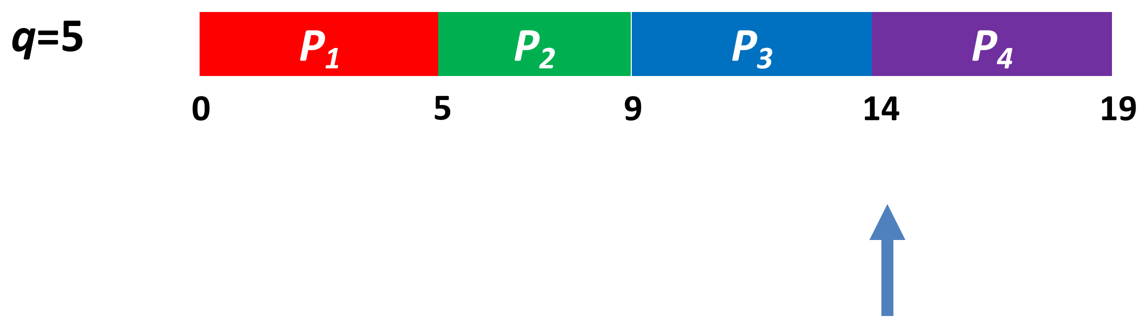


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

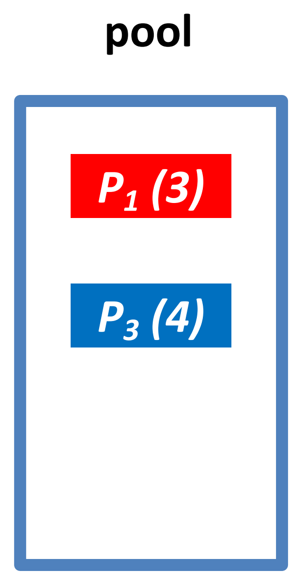


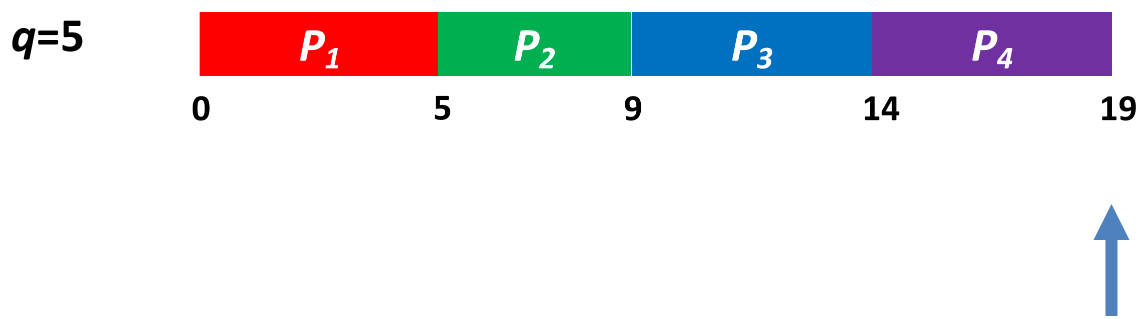


Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

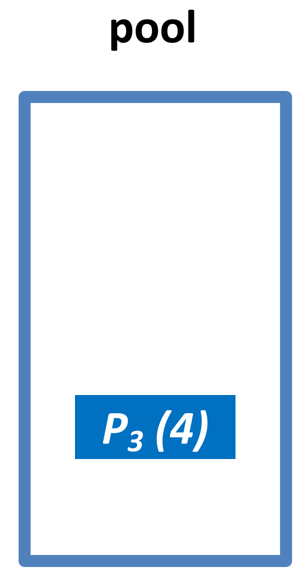




Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5



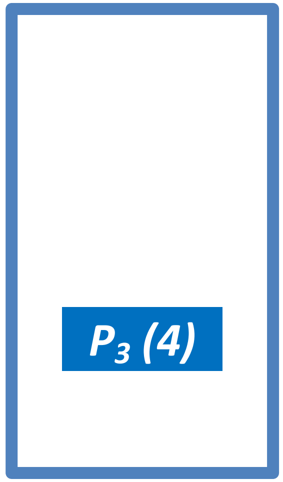
q=5

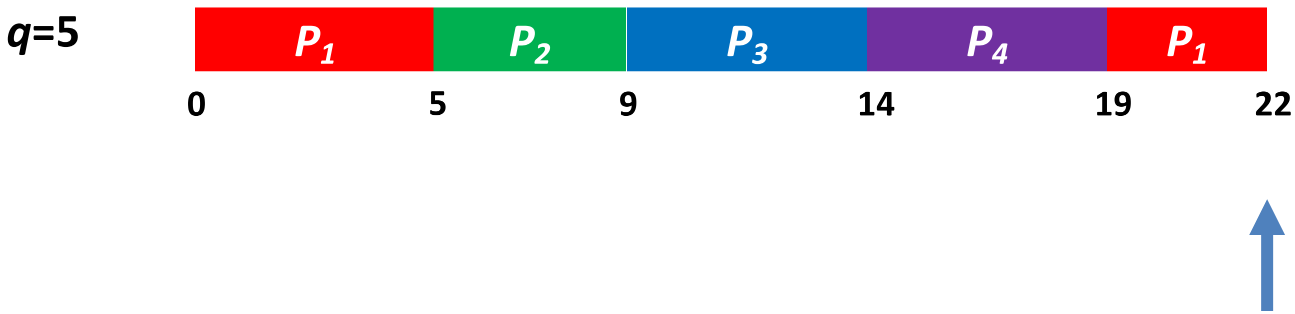
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

pool





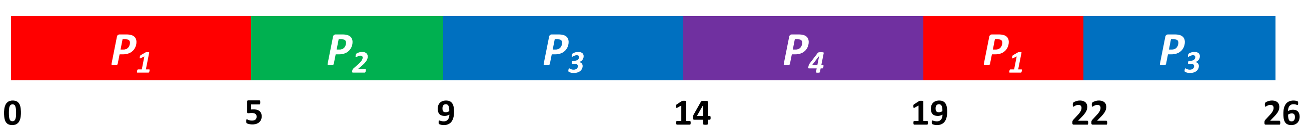
Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

pool

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

***q*=5**



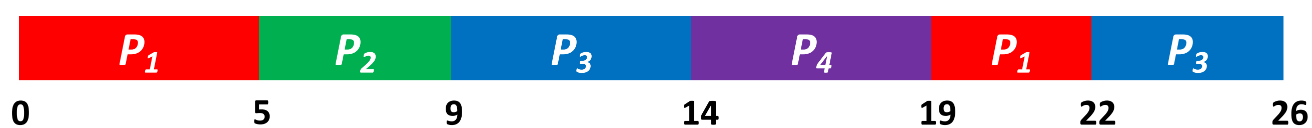
Round Robin (RR)

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

***q*=5**



Average turnaround time = ?

Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
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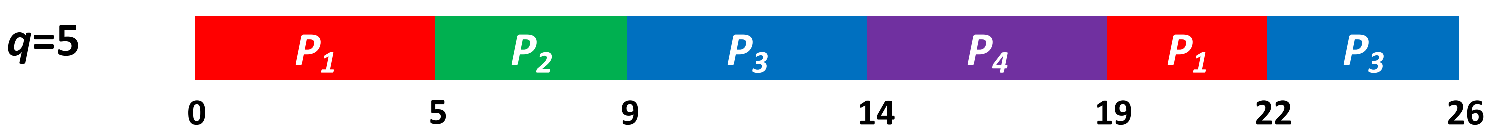

Average turnaround time = ((22-0)+(9-1)+(26-2)+(19-2)) / 4 = 17.5

Round Robin (RR)

Turnaround time = End time – Arrival time
Response time = Start time – Arrival time

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
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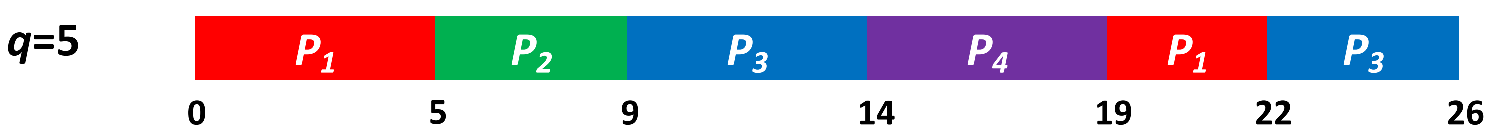


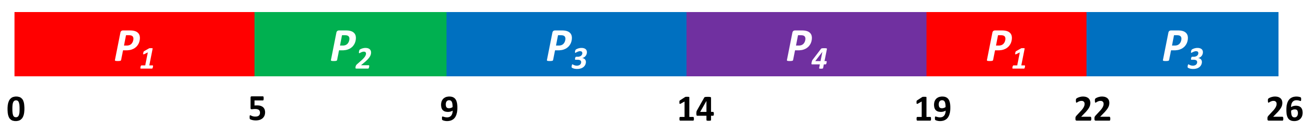
Average response time = ?

Round Robin (RR)

- Like FCFS, but with limited time slices, preemptive

Process	Arrival Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

q=5



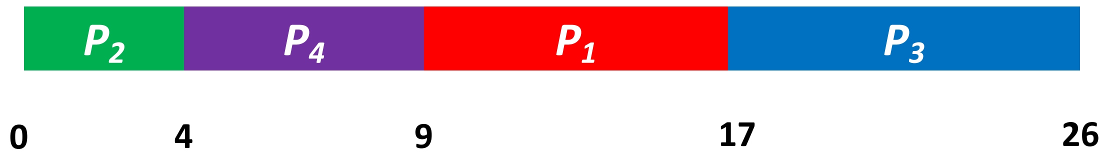
Average response time = (0+(5-1)+(9-2)+(14-3)) /4 = 5.5

Priority Scheduling

- CPU schedules the highest priority (smaller value) first, FCFS within the same priority

Process	Priority	Burst Time
P_1	3	8
P_2	1	4
P_3	4	9
P_4	2	5

Suppose arriving time is same



Priority Scheduling

- CPU schedules the highest priority (smaller value) first, FCFS within the same priority

Process	Priority	Burst Time
P_1	2	8
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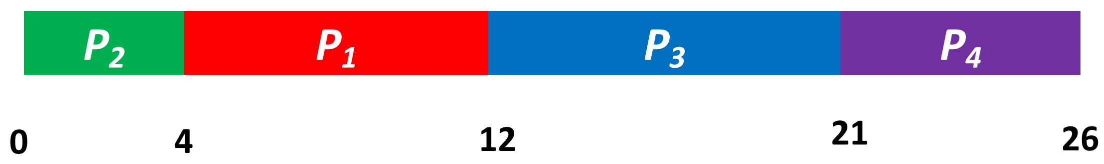
Suppose arriving time is same



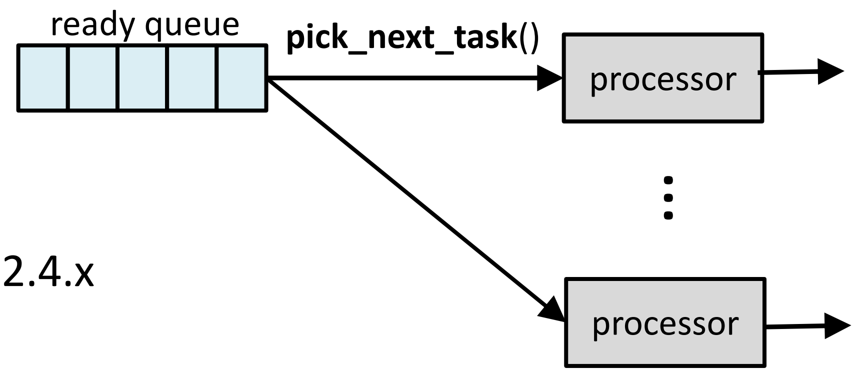
Comparison

	Turnaround time	Response time
FCFS	15.25	8.75
SJF-preemptive	**13**	**4.25**
RR (q=5)	17.5	5.5
Priority scheduling	N/A	N/A

	Throughput	Response time	Starvation
FCFS	TBD	TBD	No
SJF-preemptive	High	Good	Yes
RR	Can be low	Good	No
Priority scheduling	Can be high	Can be good	Can remove

Challenges on Emerging Hardware and Applications

- Multi-processor → Single queue



Linux 2.4.x

Multiprocessor = more powerful processor

pick_next_task() will be the bottleneck

Pros:

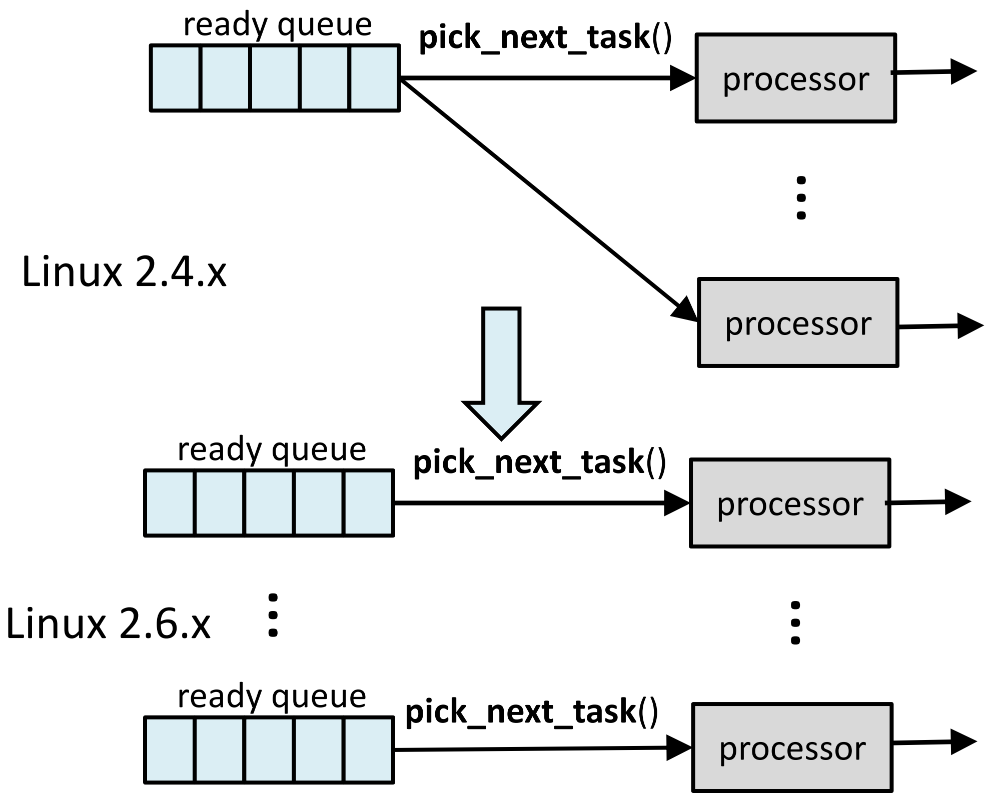
1. Easy to implement
2. Perfect load balancing

Cons:

1. Scalability issues due to centralized synchronization
2. High overhead and low efficiency
3. Hard to maintain cache hotness due to global scheduling

Challenges on Emerging Hardware and Applications

- Multi-processor → Many queues



Multiprocessor = more powerful processor

pick_next_task() will be the bottleneck

Pros:

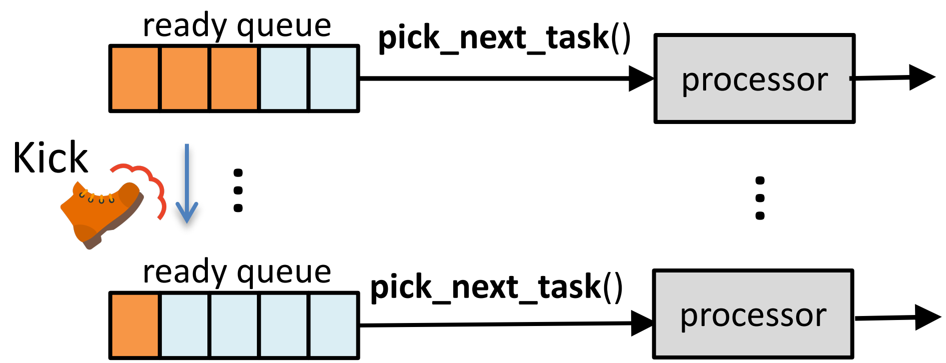
1. Scalable to many CPUs
2. Easy to maintain cache hotness

Cons:

Self-scheduling, could have load imbalance

Overcome Load Imbalance

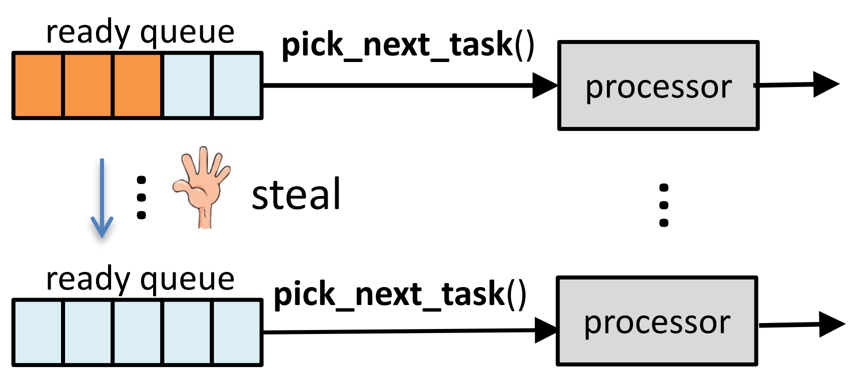
- Push model



Every a while, a kernel thread checks load imbalance and move threads

Made by OS

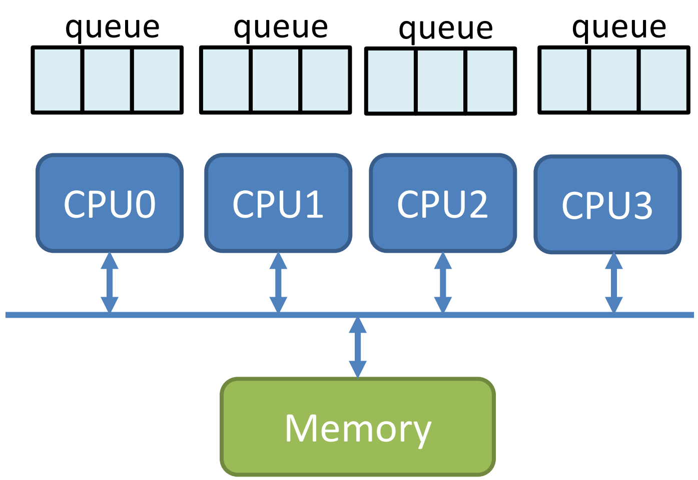
- Pull model



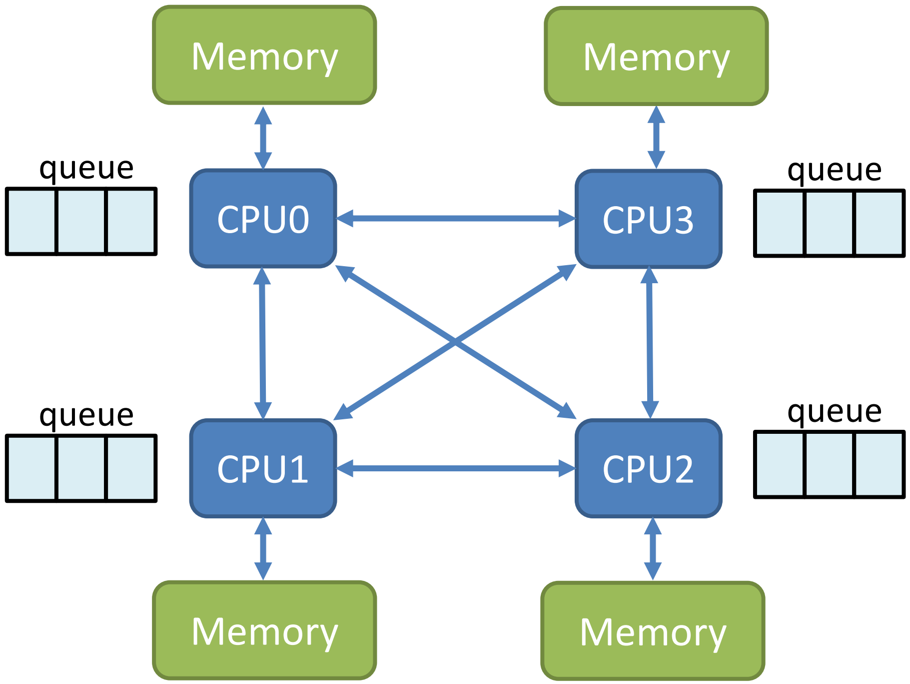
Whenever a queue becomes empty, steal a thread from non-empty queues

Made by local queue. Both are widely used

Load balance on SMP vs. NUMA



symmetric multiprocessing (SMP):
The distance to memory is the same



Non-uniform memory access (NUMA):
The distance to memory is different

Multi processor/core scheduling

The scheduling policy not only considers the fairness, throughput, etc., but also needs to consider the **hardware architecture** (e.g., locality)

Conclusion

- Introduction to CPU scheduling
  - What is CPU scheduling
  - Why we need CPU scheduling
  - When scheduling happens
- Scheduling policies
  - FCFS, SJF, RR, Priority
  - Scheduling on multiple CPUs