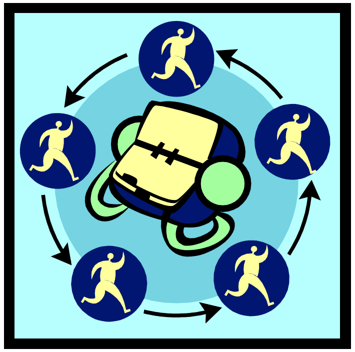
CIS 520, *Operating Systems Concepts*

Lecture 2

Process (CPU) Scheduling

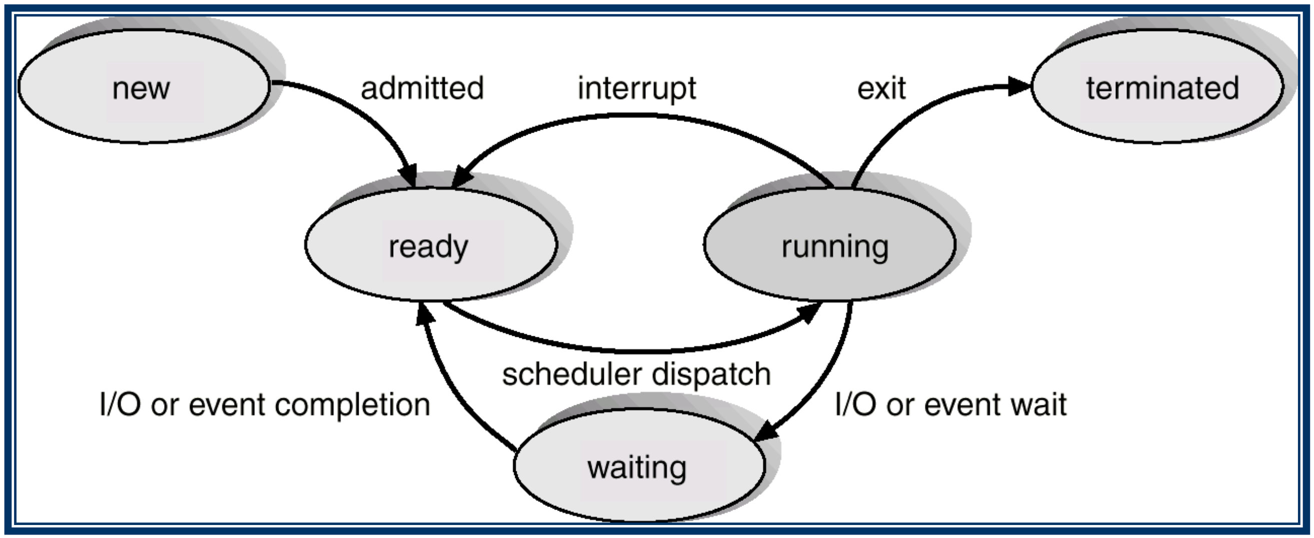


Igor Faynberg

Why “Process (CPU)”?

- Well, we really schedule *processes* and by doing so, we *allocate* a CPU to each process
- We can also say that we schedule the CPU time among the processes
- So, both terms *process scheduling* and *CPU scheduling*, mean the same thing
- We will use both terms interchangeably

Remember the Process States?



How Many Processes are in the *Running* State?

- Typically, there are about as many as there are CPUs to execute them (although one CPU could be kept just for executing the operating system)
- If there is one CPU—our assumption for the rest of the day—only one process can be running

So, What Causes a Transition out of *Running*?

- In older systems, only three things:
  1. Waiting for an I/O [transition to *waiting*]
  2. Executing an illegal instruction or accessing non-existing address, which resulted in the termination of the process [transition to *terminated*]
  3. Finishing execution (natural transition to *terminated*)

- But waiting could be—and was—generalized to waiting for any condition (which is what semaphores do)
- In systems that do only data-processing (which is I/O-heavy), just that could be sufficient, but what to do with a process that solves a linear programming problem for 17 hours and then just prints the solution?

A Note on Interrupt Processing

- And what happens when a *running* process is interrupted—say, by an I/O device which completed the action that another process was waiting for?
  - In some systems, the other process would transition to *ready* and move to the *ready* queue, but the CPU would be returned to the process that was running
  - Yet, another solution may be to transition the *running* process to *ready* and then select the new running process from the ones that have been ready.

Preemptive schemes (Time Slicing)

- Back to the *CPU-bound* processes: to co-exist among themselves (as well as with the *I*/O-bound ones) they must be *preempted* when they exceed their time quota (*time slices*)
- For that, hardware must support a *timer* (or an *alarm*), which would issue an appropriate interrupt

Time Slicing (cont.)

- Preemptive schemes require more frequent context switches, so they come with a cost!
- In general, time slicing is needed to ensure fairness on mainframes and public servers, but it was not *that* much needed in PCs
- Hence, earlier personal computers' operating systems (Windows 3.1 and Apple Macintosh) did not support time slicing

Scheduling

- ***Q***: What do we do when there are more than one *ready* process?
- ***A***: We queue them (in the *Ready* Queue) and then select the one to run (for each available CPU—but let us assume for now that we have one CPU), according to a *scheduling algorithm*
- ***Q*:** What are we trying to achieve in such an algorithm?

Scheduling Criteria (some at cross-purposes with others!)

- Maximize *CPU utilization* (should be between 40% and 90%)
- Maximize *I/O device utilization* (should be between 40% and 90%)
- Maximize *throughput* (*processes/sec*)
- Minimize average (or maximum) *turnaround* time
- Minimize average (or maximum) *response* time—in interactive systems) and its variance
- Minimize average (or maximum) *waiting time* (the time spent in the *ready* queue)

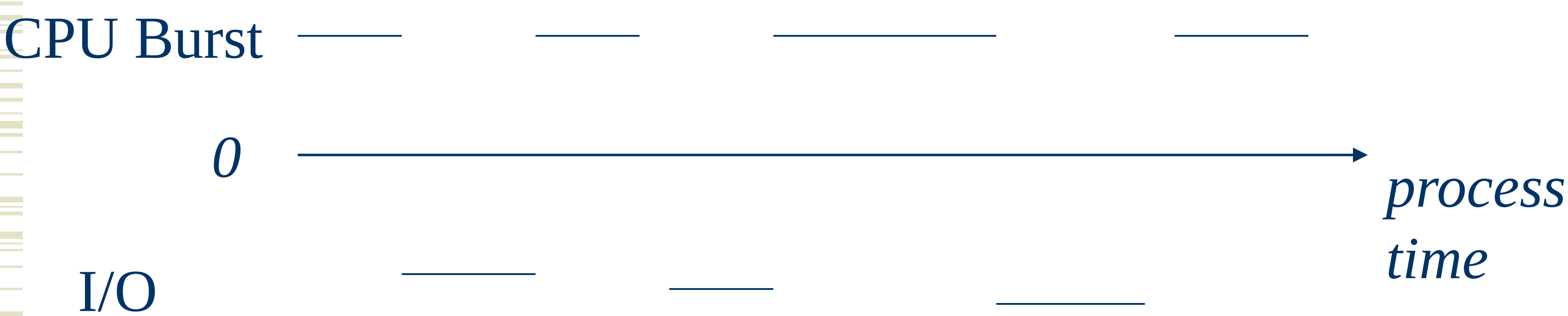
Long Term/Short Term

In the (old) batch systems user jobs were read from a device (a tape- or card reader) and stored on the disk

- Selecting the jobs to load into memory is a matter of *long-term scheduling*
- Selecting an in-memory job to run is a matter of *short-term scheduling*

CPU Burst/IO Burst

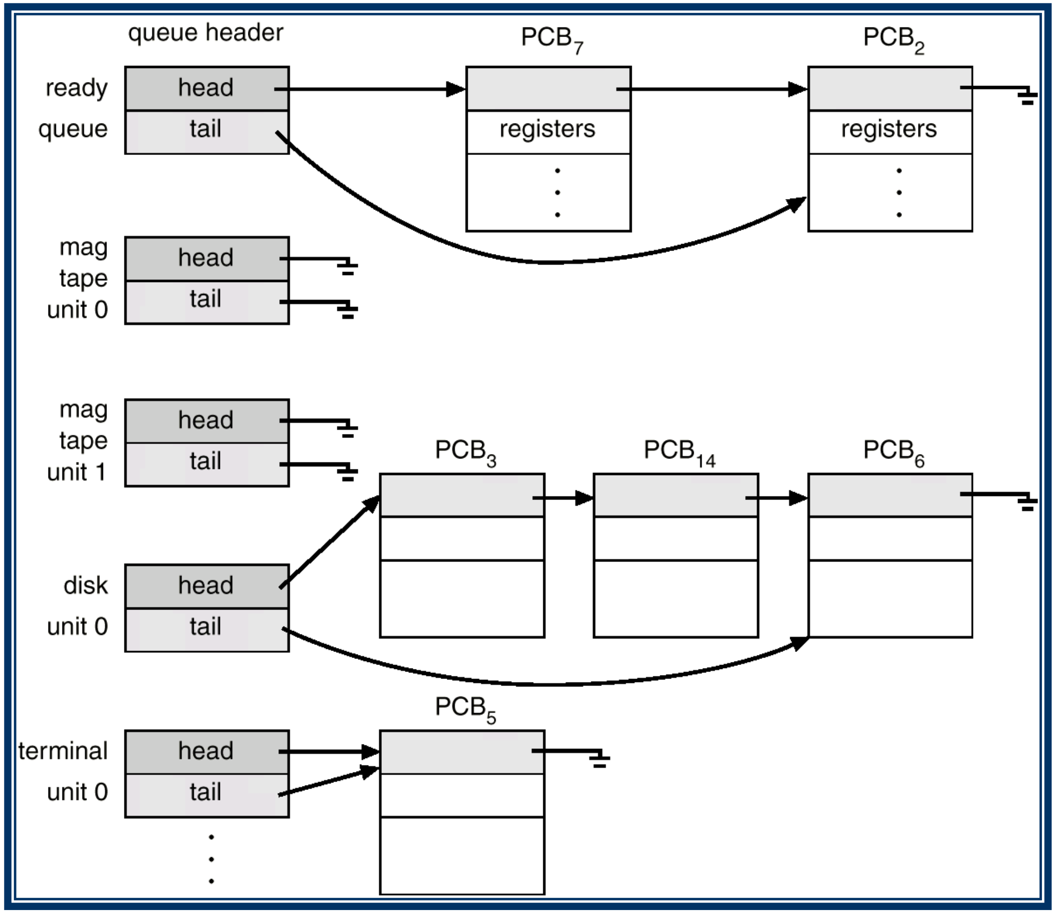
- Overall, a *useful* life of an average process is a repetition of CPU bursts followed by I/O bursts:



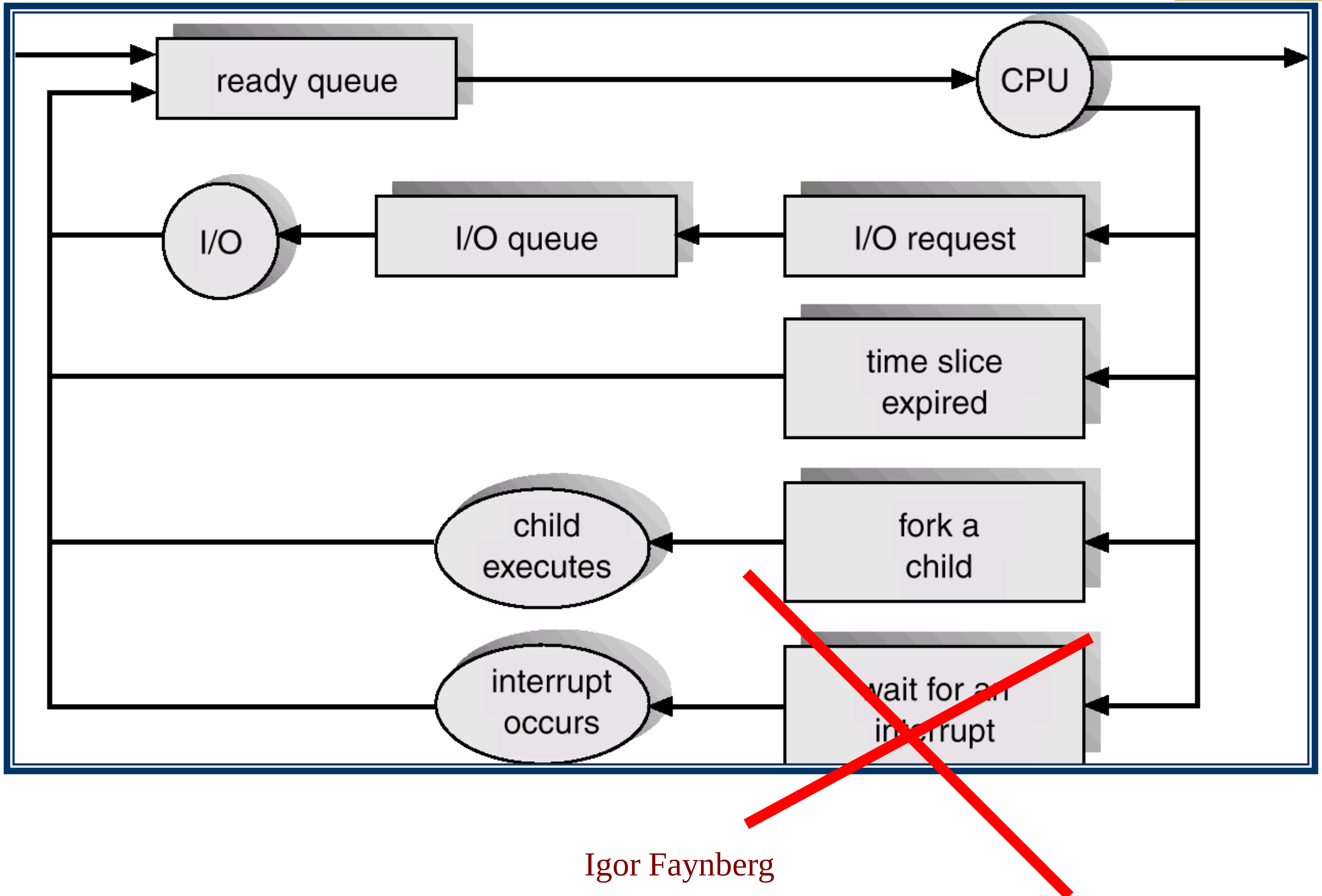
The process information is maintained in the Process Control Block (PCB)

Process ID
Process state (*ready*, *running*, etc.)
All the registers (including PC and SP)
Memory management information
File information
Children processes information
... many other things ....

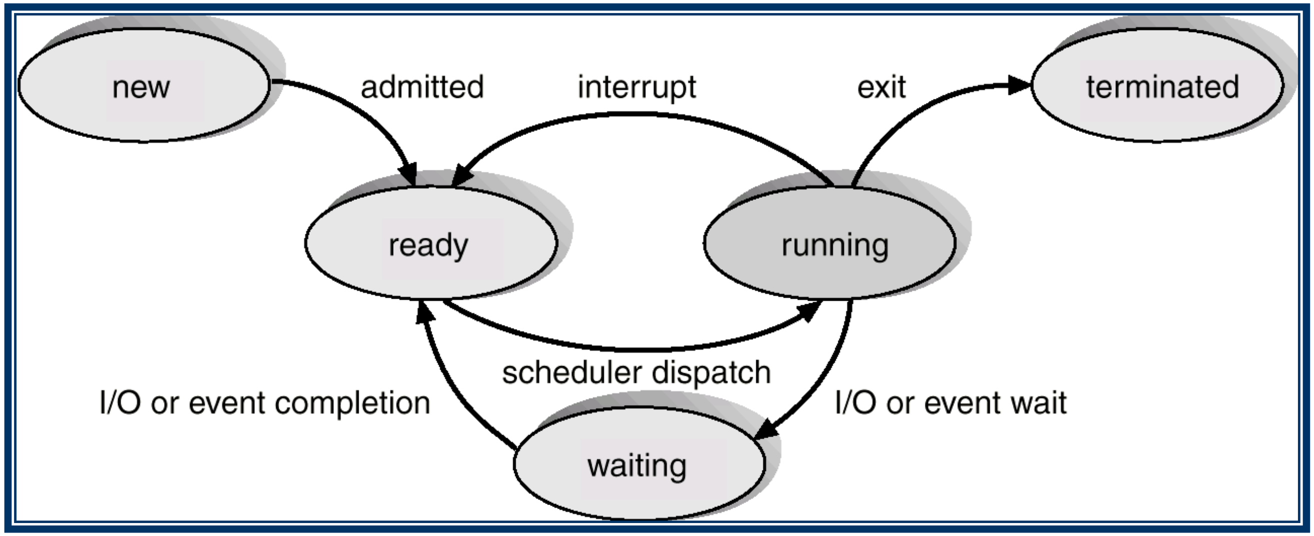
Where is This Process?



Process Scheduling (from the Book)



Back to the state machine



Scheduling Algorithms

- First-Come, First-Served (FCFS) Scheduling
- Priority Scheduling
  - Special Case: Shortest-Job-First (SJF) (or rather *Shortest Next CPU Burst First*)
- Round Robin Scheduling
- Multilevel Queue Scheduling
  - Multilevel Queue Feedback Scheduling

A Management Tool: *Gantt Chart*

P_1	P_2	P_3	…	P_n

0 t_1 $t_1 + t_2$ $t_1 + t_2 + t_3$ … $\sum_{i=1}^{n} t_i$

Execution time:

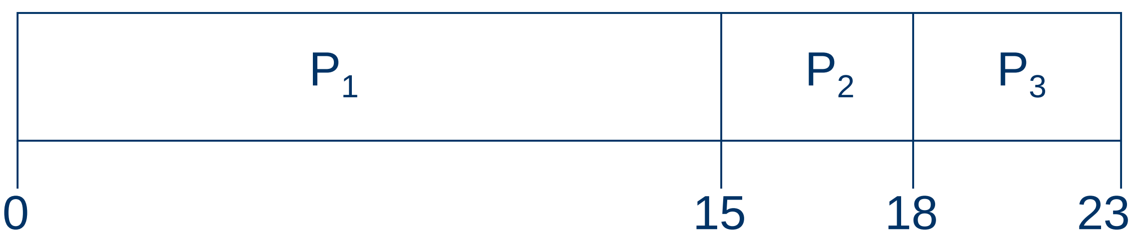
P_1	t_1
P_2	t_2
P_3	t_3.
…	
P_n	t_n

Average Waiting Time: $$\frac{1}{n}\sum_{i=1}^{n-1}(n-i)t_i$$

First-Come, First-Served (FCFS)

Process	Burst Time (in milliseconds)
P_1	15
P_2	3
P_3	5

- Suppose that the processes arrive in the order: P_1 , P_2 , P_3
  The Gantt Chart for the schedule is:

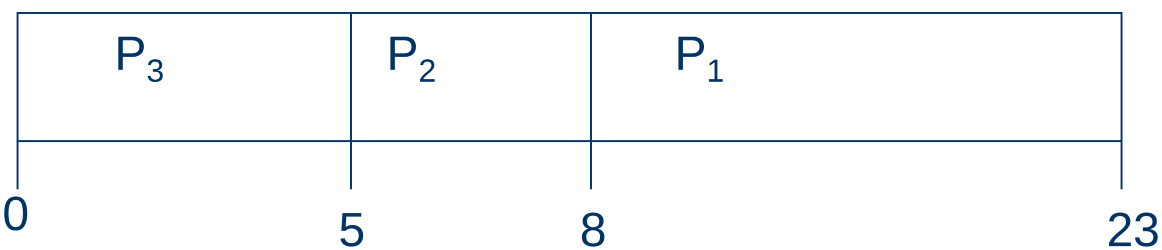


- Waiting time for $P_1 = 0$, $P_2 = 15$; $P_3 = 18$
- Average waiting time: $(15 + 18)/3 = 11$

Let us try to rearrange the processes…

Process	Burst Time
P_3	5
P_2	3
P_1	15

Then the Gantt Chart for the schedule is:

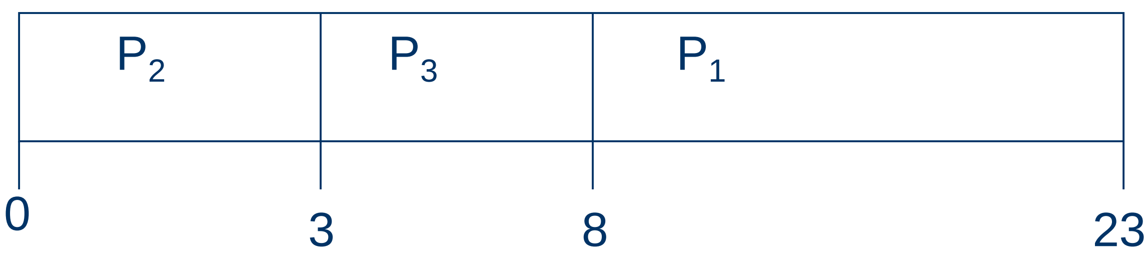


- Waiting time for $P_3 = 0$, $P_2 = 5$; $P_1 = 8$
- Average waiting time: $(5 + 8)/3 = 4\ 1/3$

Or, better yet…

Process	Burst Time
P_2	3
P_3	5
P_1	15

Then the Gantt Chart for the schedule is:



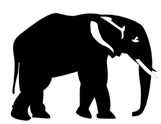
- Waiting time for P_2 = 0, P_3 = 3; P_1 = 8
- Average waiting time: (3 + 8)/3 = 3 2/3

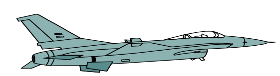
FCFS Drawbacks:

- Allows CPU-bound processes to hug the CPU
- May have a terrible effect on I/O utilization
- In the absence of pre-emption is unacceptable in a multi-user environment

Shortest Job First (SJF)

- This algorithm predicts the *next* CPU burst of a ready process and builds the queue sorted in the ascending order of the *expected* CPU bursts:





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SJF Issues

- It is optimal as far as waiting is concerned: it minimizes the average waiting time for a given set of processes (as you will prove when doing homework!)
- But then it depends on predicting the CPU burst times

But *how* do we predict the next burst? (An **important** technique to remember!)

- *Exponential Averaging:*

CPU Burst **Actual**	t_0	t_1	t_3	…	t_n
Predicted	τ_0	τ_1	τ_2		τ_n

time

$$\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n,$$

$$0 \le \alpha \le 1$$

τ_0 is guessed or selected randomly

Exponential Averaging

- Is a *smoothing* mechanism
- Is applicable to many domains [e.g., signal processing, operating systems, Internet transport (TCP), and Internet QoS in routers]
- Stores the past history: $\{t_k\}_{k=1}^{n-1}$
- Assigns lower weights to more remote terms:

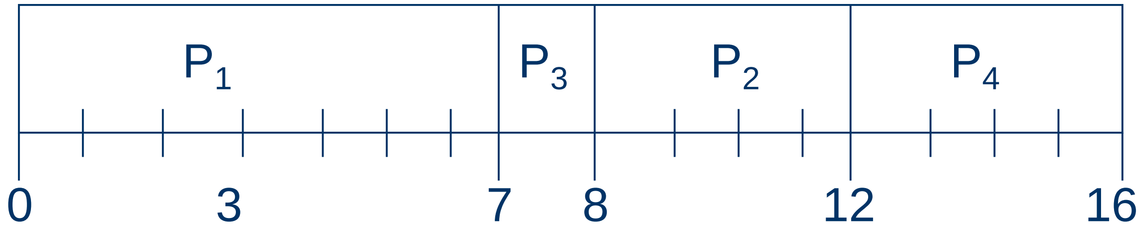
$$\tau_{n+1} = (1-\alpha)^{n+1}\tau_0 + \alpha\sum_{k=0}^{n}(1-\alpha)^{n-k}t_k$$

Preemption in SJF: SRTF

- SJF can be either *preemptive* or *non-preemptive*
- When the process with a shorter CPU burst than what remains for the currently running process arrives into the ready queue, a choice can be made to preempt the running process. The resulting scheduling discipline is called *Shortest-Remaining-Time-First (SRTF)*
- ***NB: The decision is made only when 1) a new process arrives or 2) when a process has finished its execution.***

Example of Non-Preemptive SJF

Process	Arrival Time	Expected Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	6	4

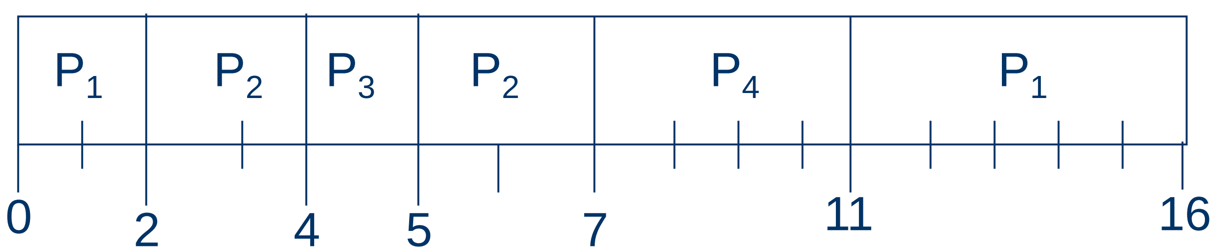


- Average waiting time = (0 + 6 + 3 + 6)/4 = 3 3/4

Example of SRTF

Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	6	4

- The Gant chart:



- Average waiting time = (9 + 1 + 0 +1)/4 = 2 3/4

Priority Scheduling

- Here, a number (*priority*) is assigned to each process, and the processes are scheduled so that the process with the highest priority runs first
- We *define* that a smaller number designates a higher priority ($2 \succ 5$), but it could be defined the other way around
- SJF is a type of priority scheduling, where the expected burst time is used as the value of priority

Assignment of Priorities

- Priorities can be assigned *internally* by the operating system (e.g., all OS activities: device managers, scheduler, etc. have higher priorities than user processes)
- Priorities can be also assigned *externally* (e.g., by a price a user pays or a user's relative importance)

A problem with Priority Scheduling

Starvation (indefinite blocking): A process is waiting for a CPU (in a *ready*) state, but it never gets it, because new processes with higher priority always come in

A solution: *Aging*, which increases the priority of a waiting process after a certain period of time it spent in a ready queue; thus, each process will eventually get a sufficiently high priority to run

Time slicing: Round-Robin (RR)

- With the methods we dealt with so far, the preemption occurred *only* when a new process arrived
- With *time slicing*, a process may be pre-empted after it ran for a defined period of time—a ***time slice*** (also called a ***quantum***)
- When a pre-empted process is simply put back into the *ready* queue, the scheduling algorithm is called ***Round Robin (RR)***

Example of RR with Time Quantum = 20 *msec*

Process	Burst Time	Runs
P_1	53	53, 33, 13
P_2	18	18
P_3	59	59, 39, 19
P_4	43	43, 23, 3

- The Gantt chart:

P_1	P_2	P_3	P_4	P_1	P_3	P_4	P_1	P_3	P_4

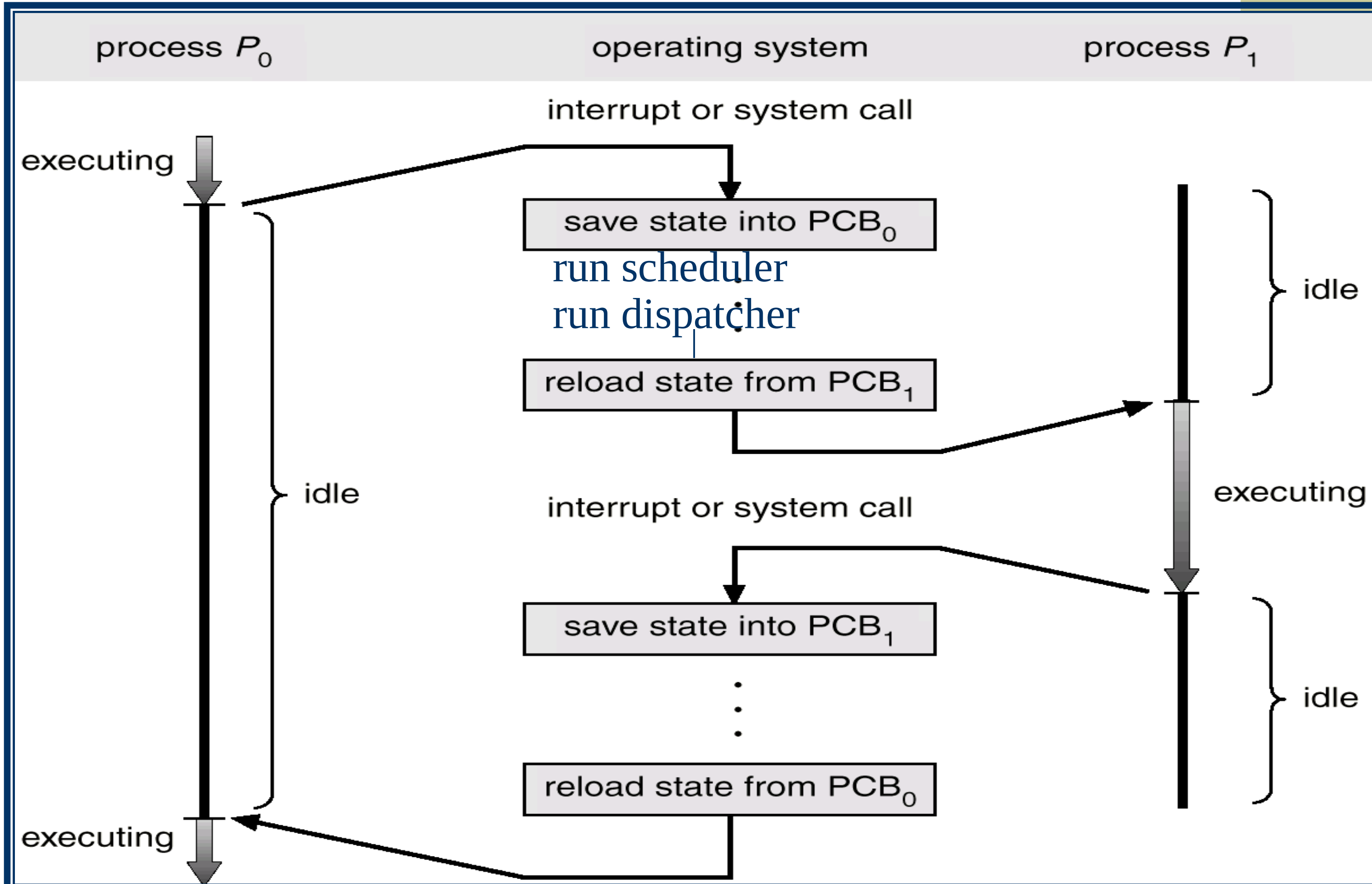
***t*:**	0	20	38	58	78	98	118	138	151	170	173
Time left:		33	0	39	23	13	19	3	0	0	0

Some observations about RR

- If a slice is large (i.e., larger than the what it takes for the longest process to execute, RR is equivalent to FCFS)
- If there are *n* processes in the ready queue, and the quantum, *q msec*, is much smaller than than the shortest process' execution time, then each process gets *1/n* of the CPU time and waits for its next turn for *(n-1)q msec*
- But...

What is involved in preemption?

After the Book



Scheduling and Context Switching Time vs. Quantum

- Scheduling and Context Switching (SCS) take time (which is why they must be programmed as efficiently as possible!)
- If the time slice is comparable to that of SCS, the overhead is unbearable:
  - Say, one process needs time T to execute
  - q is the quantum, c is the context switching time
    - $T + \frac{T}{q}c$ is needed. If $c = q$, *50%* of CPU is wasted!

Context Switch Time

- Typically varies from 1 to 1000 microseconds
- May be significantly decreased by the hardware (CDC and *Sun UltraSPARC* CPUs provide multiple sets of registers)
- Can be further decreased using *threads*

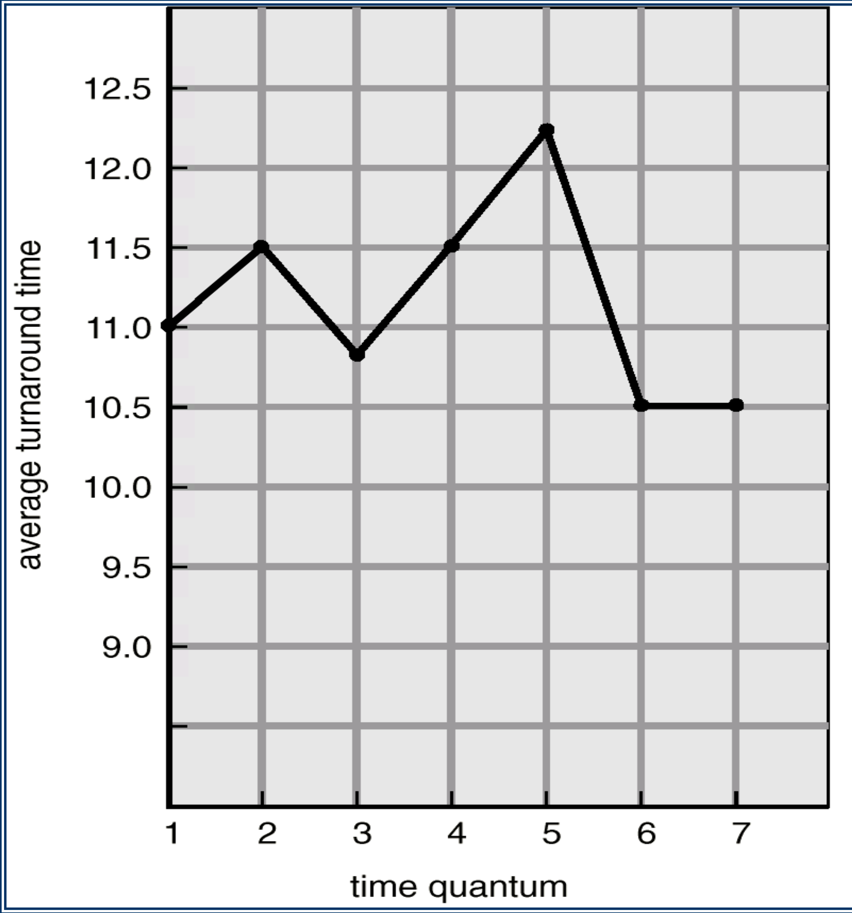
The Rule of Thumb

- The scheduling and context switching time (SCS) time is known, so the quantum should be selected appropriately
- Yet it may not be too large, or RR will degenerate into FCFS!

👍 q > 80% of a CPU burst

The effect of the quantum selection on Turnaround Time

Note: The SCS time is 0

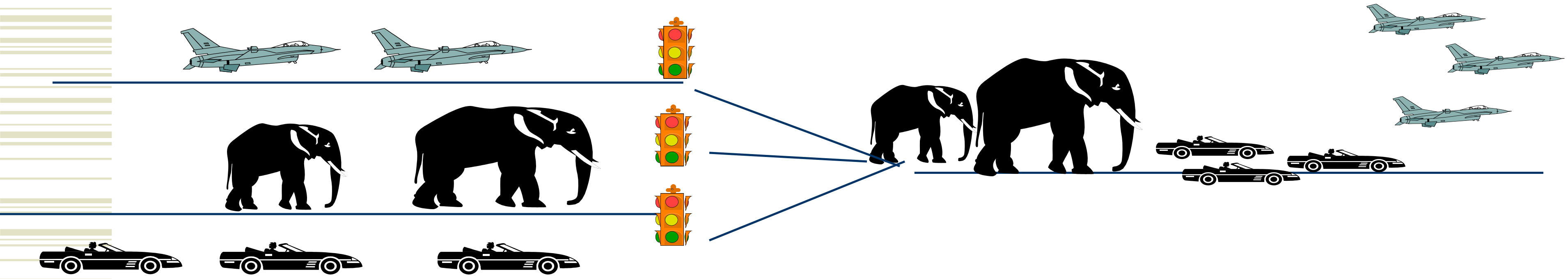


process	time
P_1	6
P_2	3
P_3	1
P_4	7

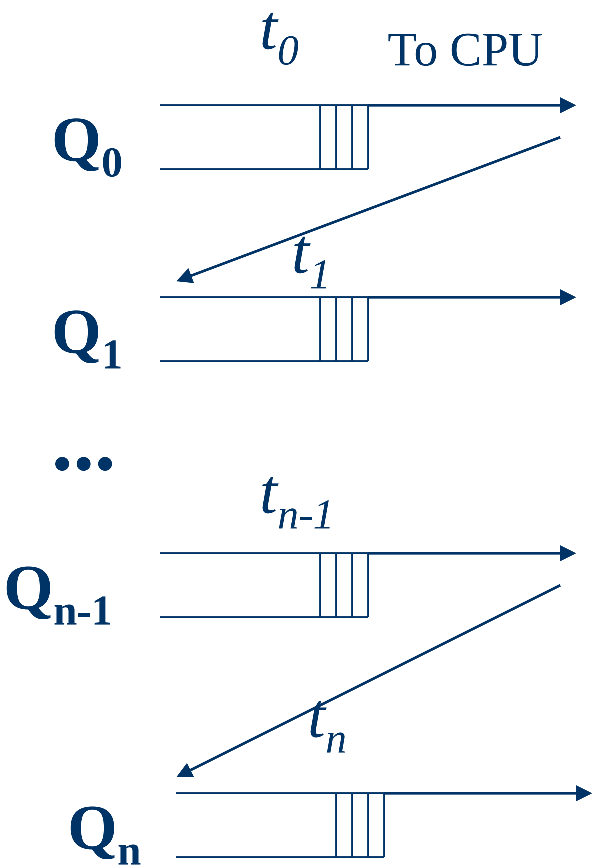
Multilevel Queue Scheduling

- Ready queue is partitioned into separate queues:
  foreground (interactive)
  background (batch)
- Each queue has its own scheduling algorithm:
  foreground – typically, RR
  background – typically, FCFS
- The scheduling selects among the queues:
  - Fixed priority scheduling; (i.e., serve all from foreground then from background, which leaves the possibility of starvation for background processes.
  - Time slice – each queue gets a certain amount of CPU time which it can distribute among the processes (for example, 80% to foreground in RR and 20% to background in FCFS)

Multilevel Queue Scheduling



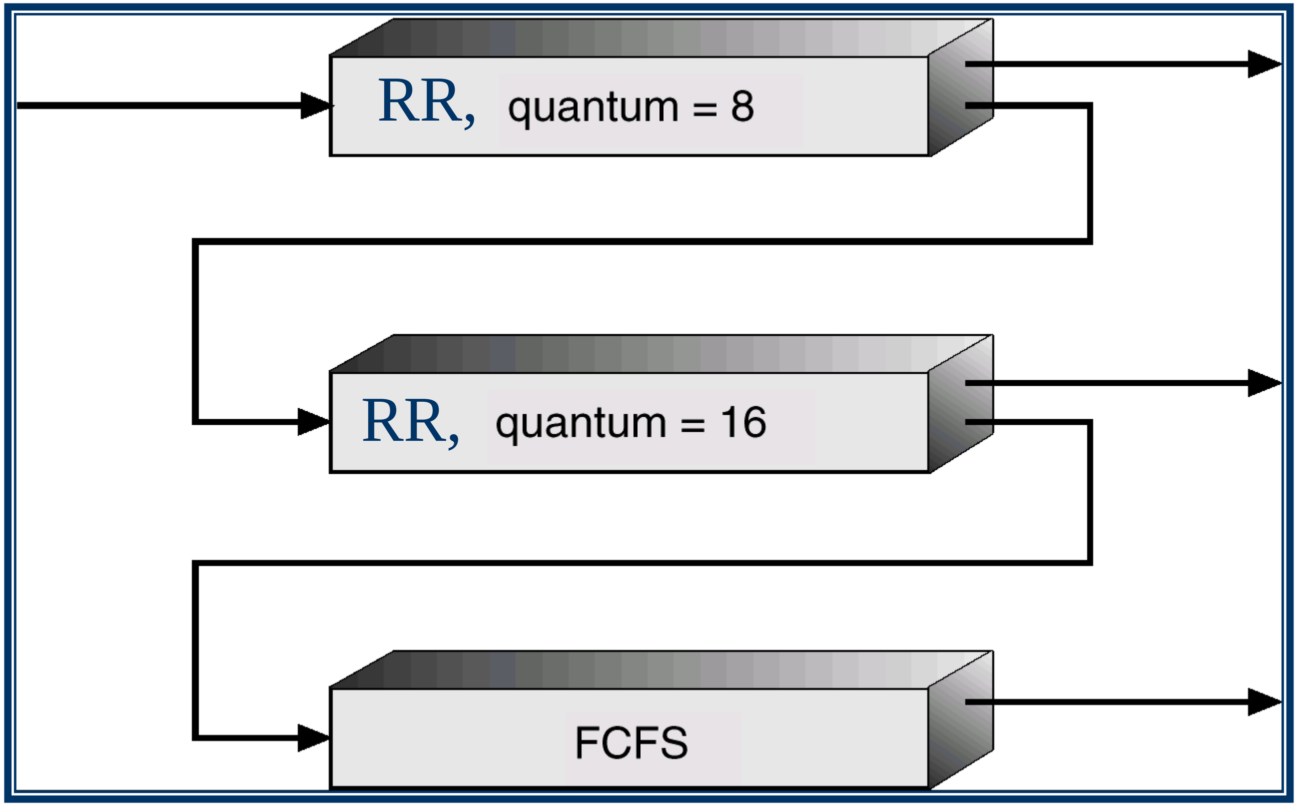
Multilevel Feedback Queue Scheduling—a variation of aging



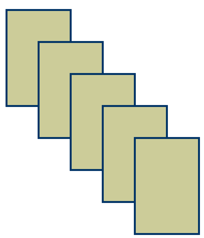
Processes in Q_i have a higher priority than those in Q_{i+1}. Until Q_i is empty, Q_{i+1} can not execute. But once a process has used its time slice, t_i, it is moved into Q_{i+1} instead of back to Q_i, and, of course, $t_i < t_{i+1}$.

An Example

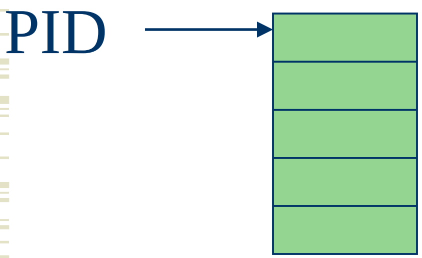
After the Book



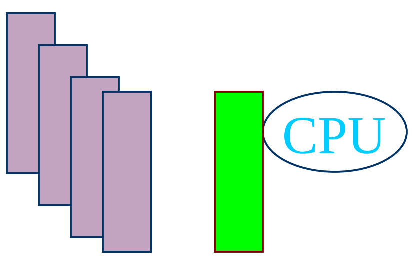
Attachment Simulation (for HW #4): *Common Data Structures*



Event List (sorted by time)



Process Control Block (PCB) (indexed by PID)



The *CPU* and *Ready Queue*

Simulation: FCFS

- Two types of events: process *arrival* and process *completion*:

```
arrival:
     {
       create a PCB entry;
       if CPU is free
          {
            mark it busy;
            PCB.state=running;
            schedule completion;
            ...
          }
       else
          {
            PCB.state=ready;
            Update the Ready Queue;
            ...
          }
```

Simulation: FCFS *(cont.)*

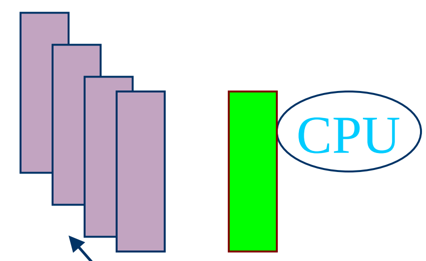
- Two types of events: process *arrival* and process *completion*:

```
completion:
     {
       destroy the PCB entry;
       if the Ready Queue is not empty
          {
            take the next process from the Ready Queue;
            select its PCB;
            PCB.state=running;
            schedule completion;
             ...
          }
       else
          {
           mark CPU free;
            ...
          }
```

Simulation: SJF

- Everything is the same as with FCFS but ***one thing***:

```
arrival:
      {
         create a PCB entry;
        if CPU is free
            {
               mark it busy;
               PCB.state=running;
               schedule completion;
               ...
            }
         else
            {
              PCB.state=ready;
              Update the Ready Queue;
              ...
            }
```

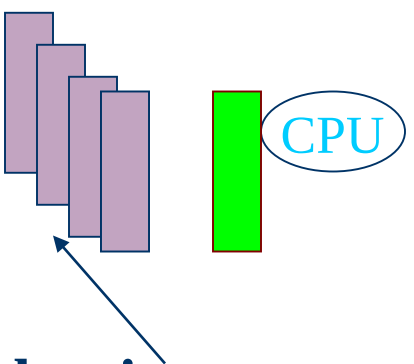


Sorted by completion times

Simulation: SRTF

- An essential difference because of preemption handling:

```
arrival:
      {
        create a PCB entry;
        if CPU is free
          {
            mark it busy;
            PCB.state=running;
            schedule completion;
            ...
          }
        else
          {
           New code;
          }
```



Sorted by time remaining to completion

Simulation: SRTF (cont.)

- The new code for the arrival case when the CPU is busy:

```
insert the job in the Ready Queue (RQ);
sort the queue by the remaining time;
compute the remaining time of the job at the CPU;
if it is greater than that of the first RQ entry then
   {
       Update its remaining time in the PCB;
       PCB.state=ready;
       Remove its completion event from the Event str.;
       Schedule the completion event for the first RQ
       entry, change its PCB.state, etc.
    }
```

Simulation: RR

- Three types of events: *arrival*, *completion*, and *timer interrupt*:

```
arrival:
     {
        create a PCB entry;
        if CPU is free
           {
              mark it busy;
              PCB.state=running;
              schedule either completion or timer interrupt;
              ...
           }
        else
           {
              PCB.state=ready;
              Update the Ready Queue;
              ...
           }
```

Simulation: RR (cont.)

```
completion: (the same as in FCFS)

timer interrupt:
     {
       Change the state and remaining time of the job
        currently running;
       Place it in the Ready Queue (FIFO in pure RR);
       Remove the first entry in the Ready Queue;
       Its PCB.state=running;
       schedule either its completion or its
      timer interrupt;
            ...
     }
```