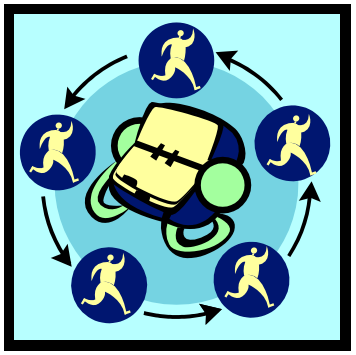
CIS 520, *Operating Systems Concepts*

Lecture 2

Process (CPU) Scheduling

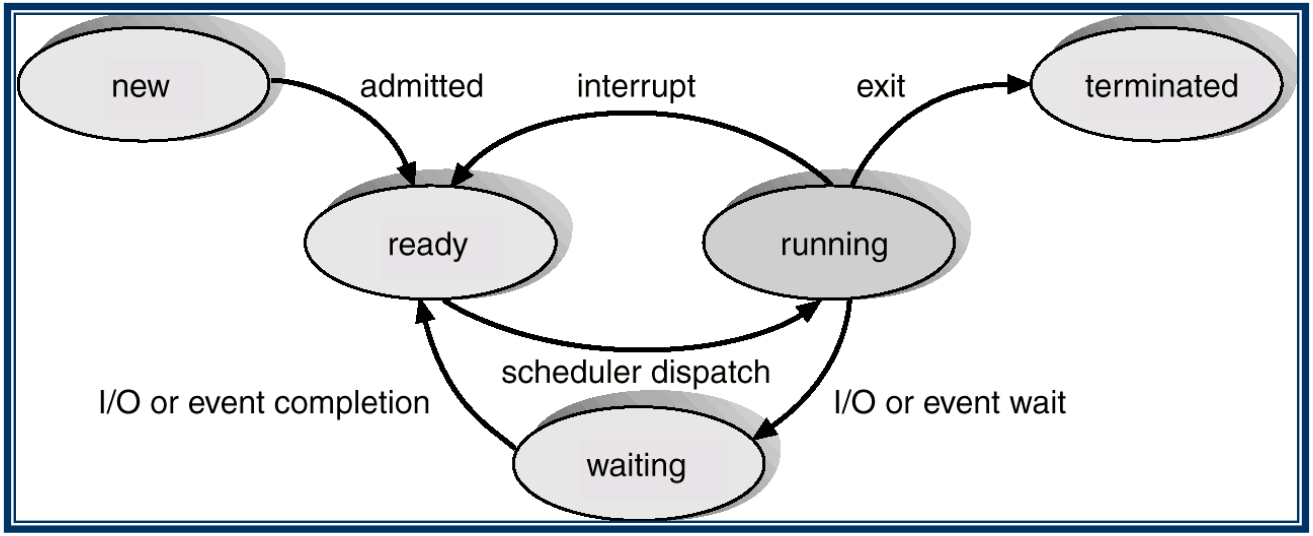


Igor Faynberg, Bell Laboratories

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)

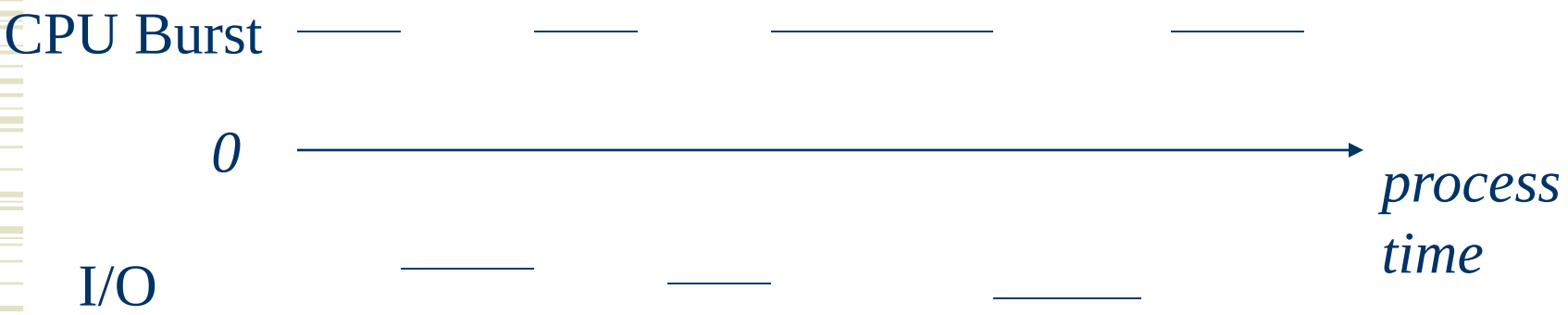
Long Term/Short Term

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

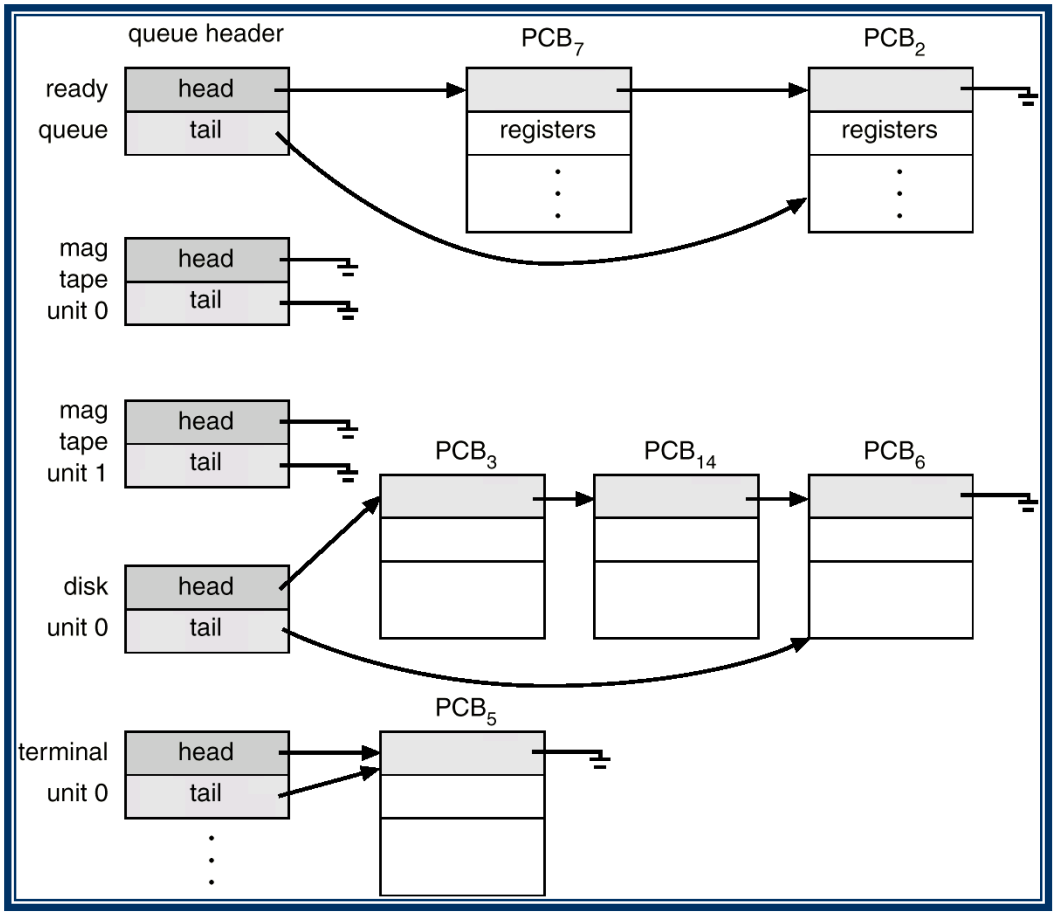
- Overall, a *useful* life of an average process is a repetition of CPU bursts followed by I/O bursts:



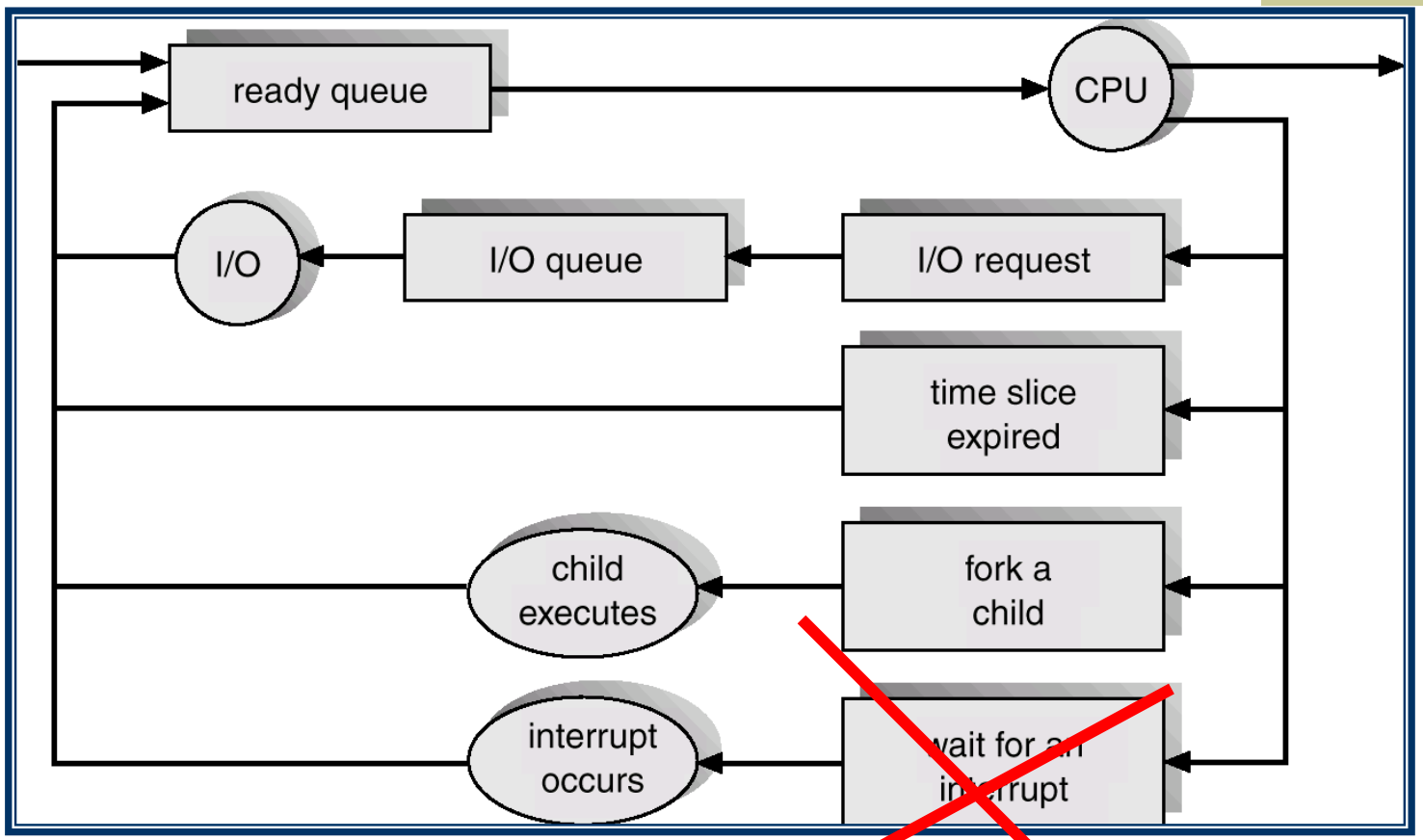
The process information is maintained in the Process Control Block (PCB)

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 ....

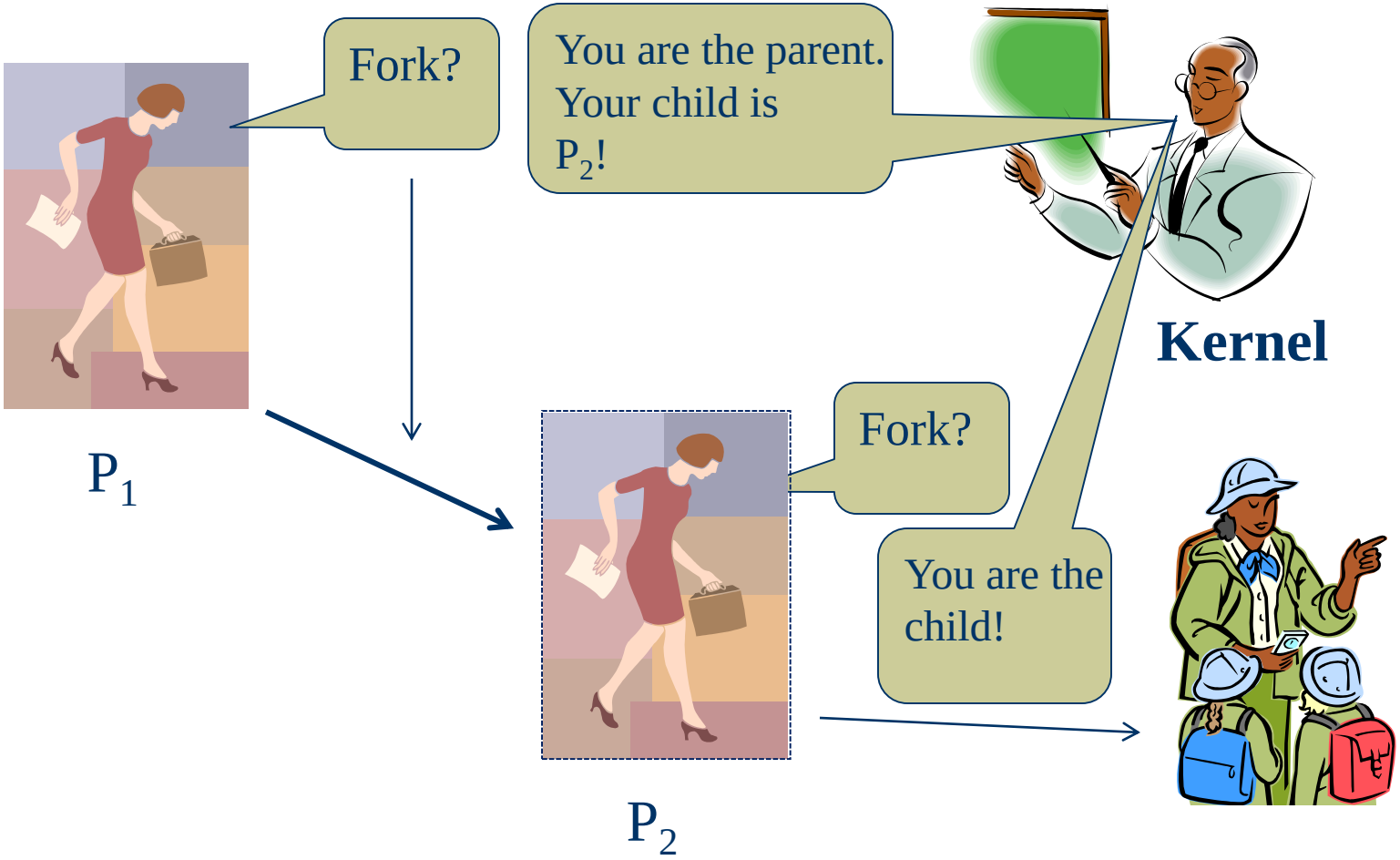
Where is This Process?



Process Scheduling (from the Book)



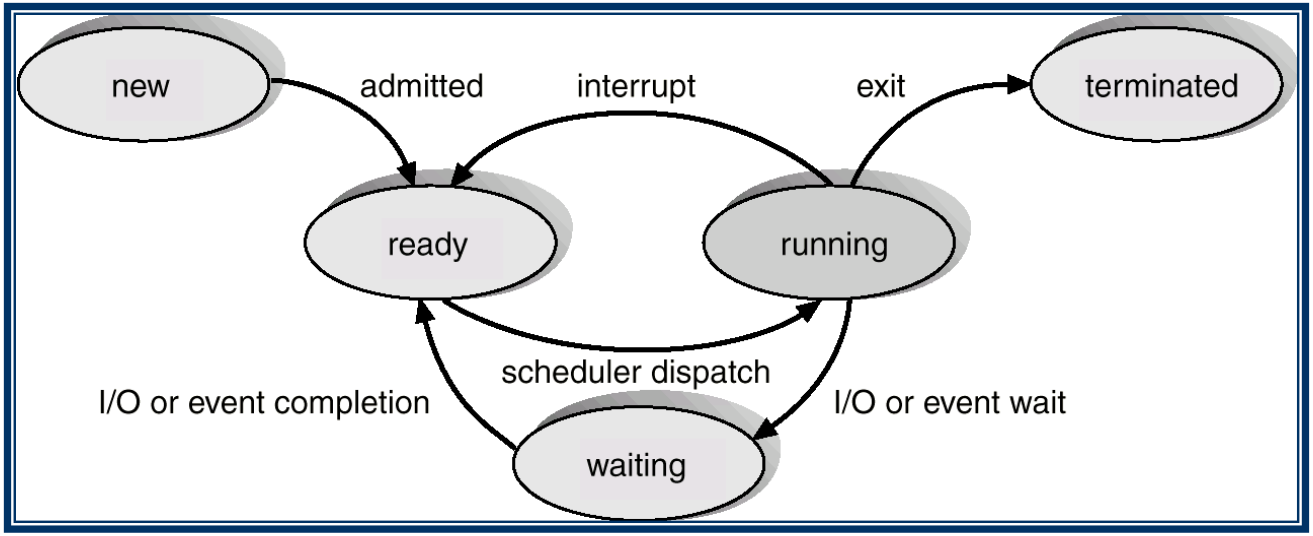
Creating a child process in Unix (or Linux)



Fork()

```
main()
  {
      int fork_result;
     fork_result  = fork();
         if (fork_result >= 0)  /* the child has been created */
           if (fork_result  == 0)  /* child */
             New_life(); _
           else
            {
             ... /* Continue old life; the child's PID is in fork_result. */
             }
         else
          ...
   }
```

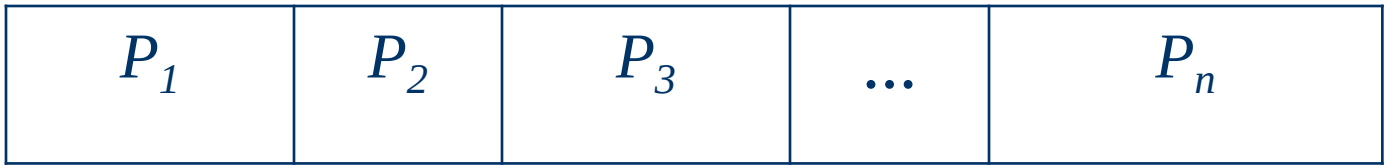
Back to scheduling!



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*



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

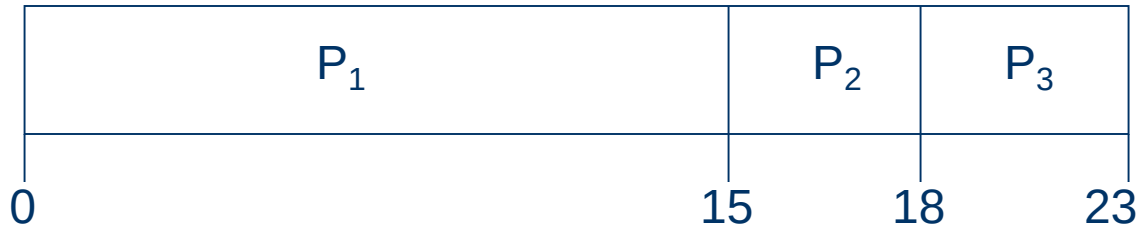
Average Waiting Time:

$$\frac{1}{n}\sum_{i=1}^{n-1}(n-i)t_i$$

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:

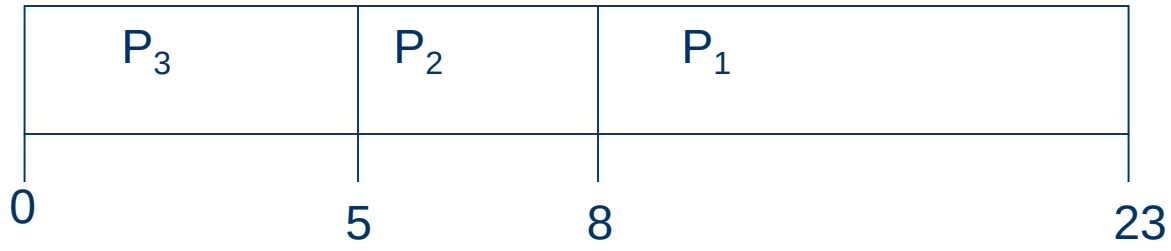


- Waiting time for P_1 = 0, P_2 = 15; P_3 = 18
- Average waiting time: (15 + 18)/3 = 11

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:

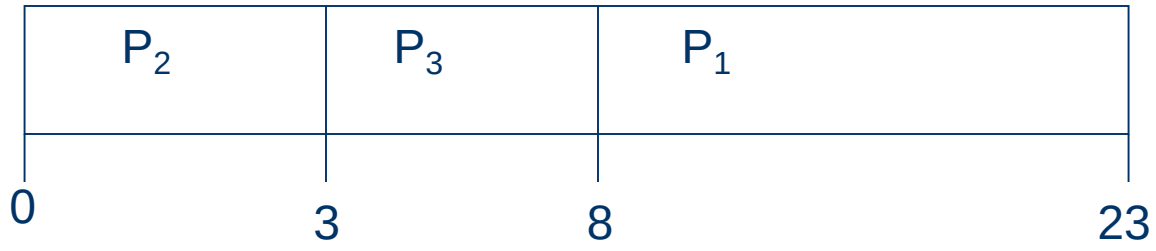


- Waiting time for P_3 = 0, P_2 = 5; P_1 = 8
- Average waiting time: (5 + 8)/3 =4 1/3

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:

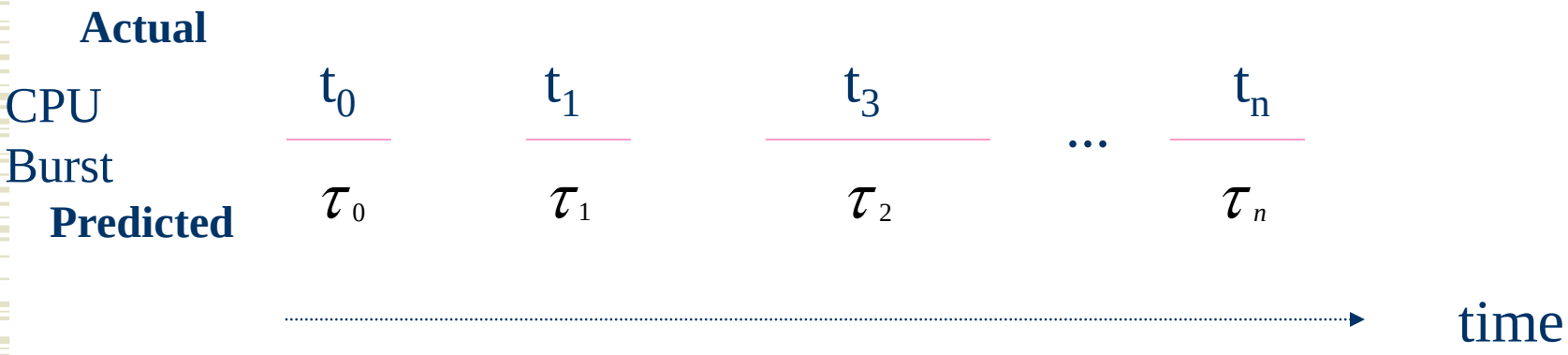
3 2 1

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:*



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

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

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:

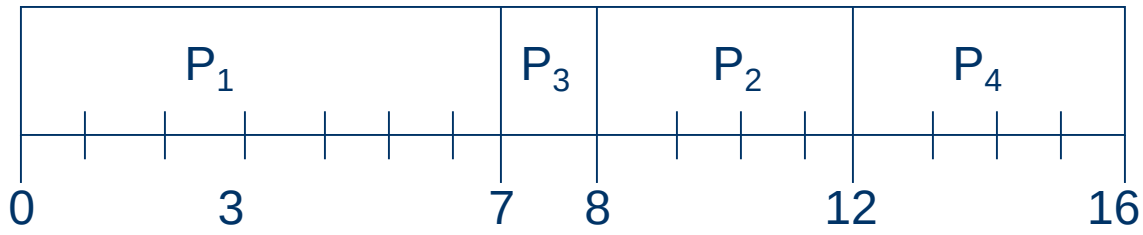
$$\tau_{n+1} = (1-\alpha)^{n+1}\tau_0 + \alpha\sum_{k=0}^{n}(1-\alpha)^{n-k}t_k$$

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

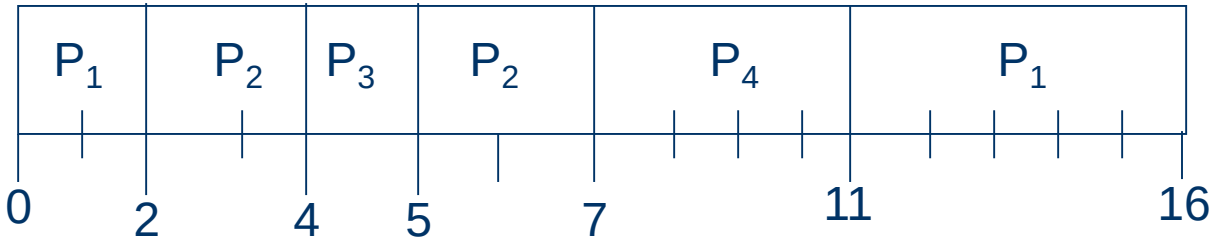


- Average waiting time = (0 + 6 + 3 + 6)/4 = 3 3/4

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:

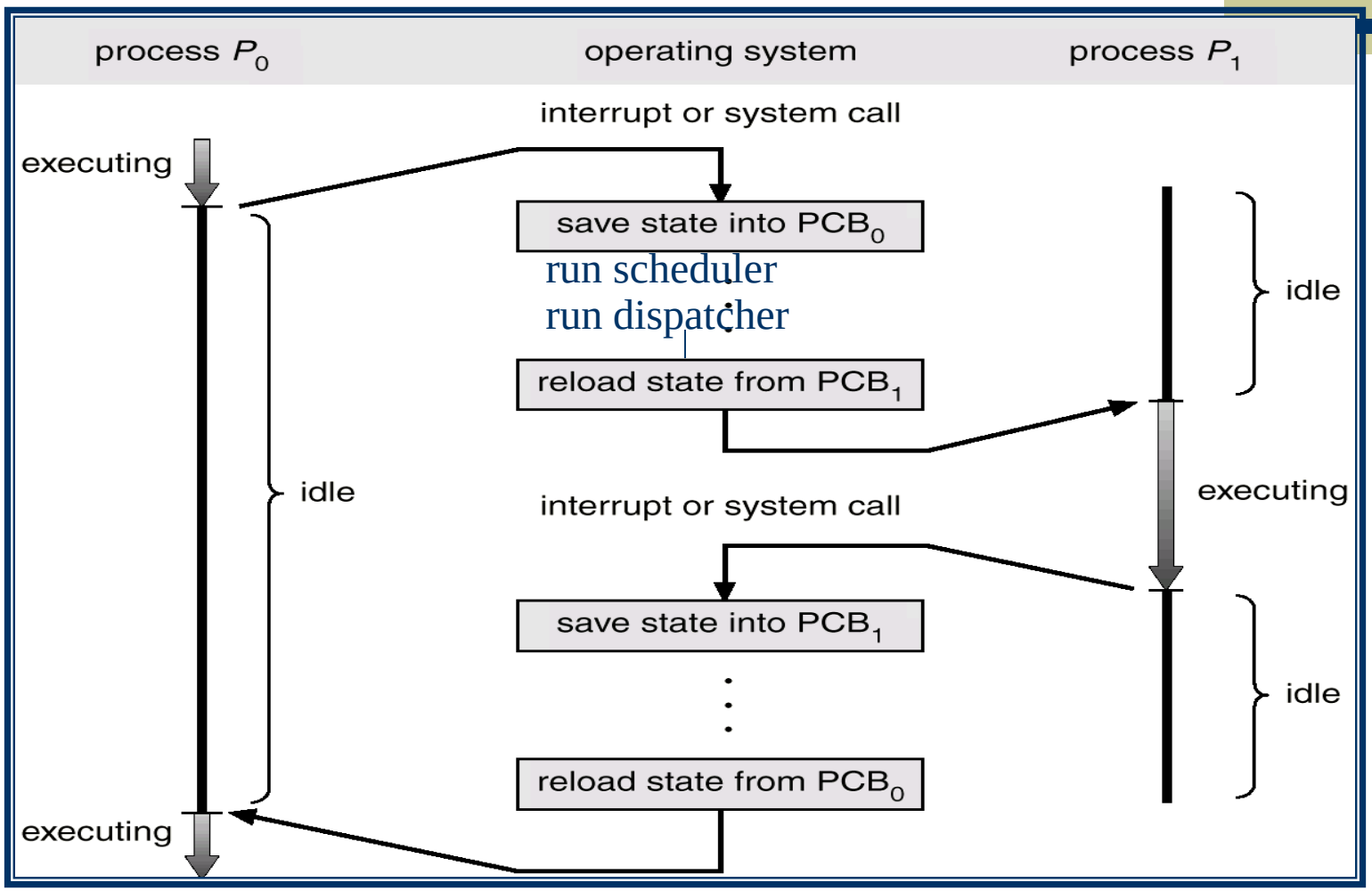
***t*:**	0	20	38	58	78	98	118	138	151	170	173
Time left:		33	0	39	23	13	19	3	0	0	0

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*

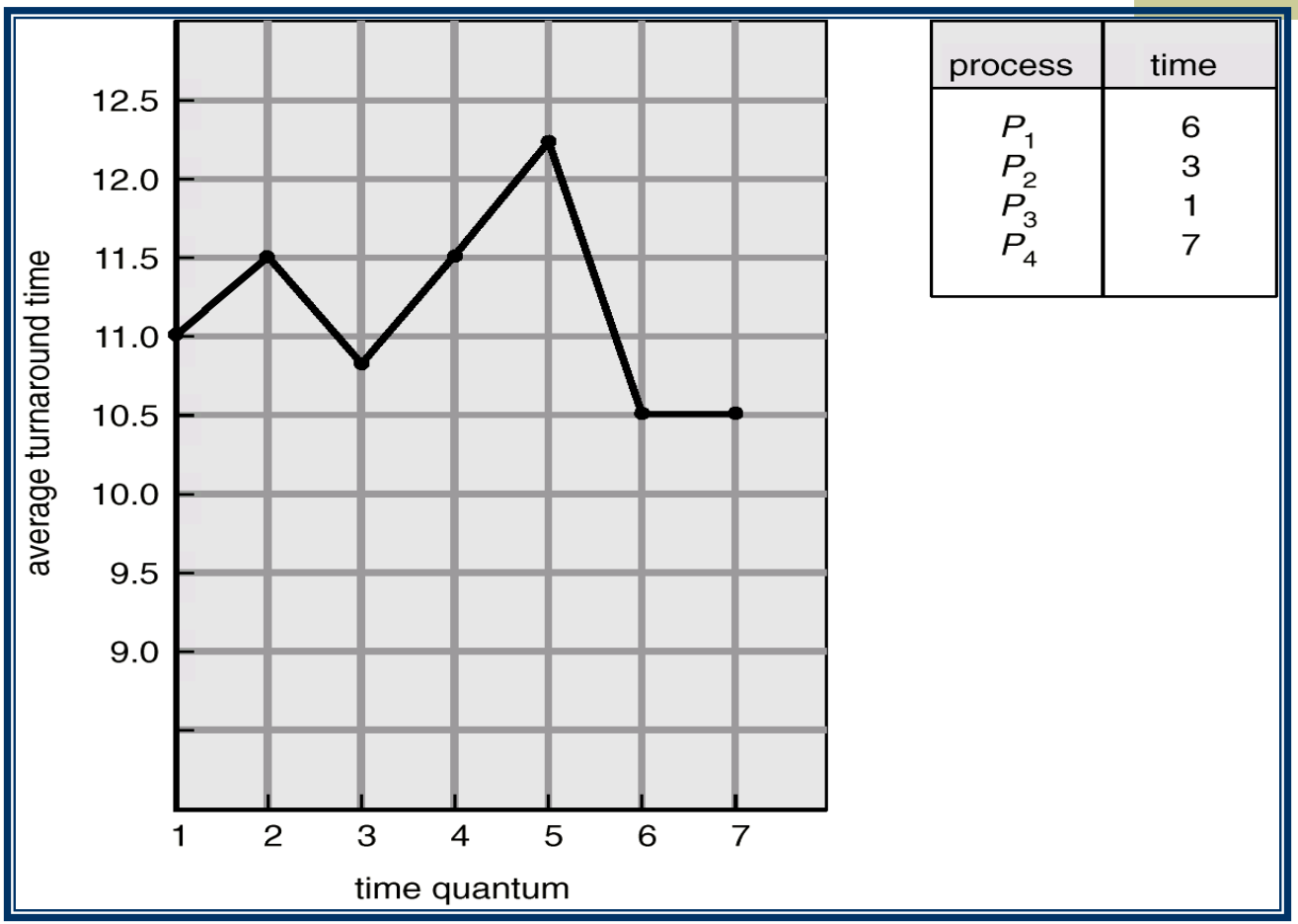
The Rule of Thumb

- 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

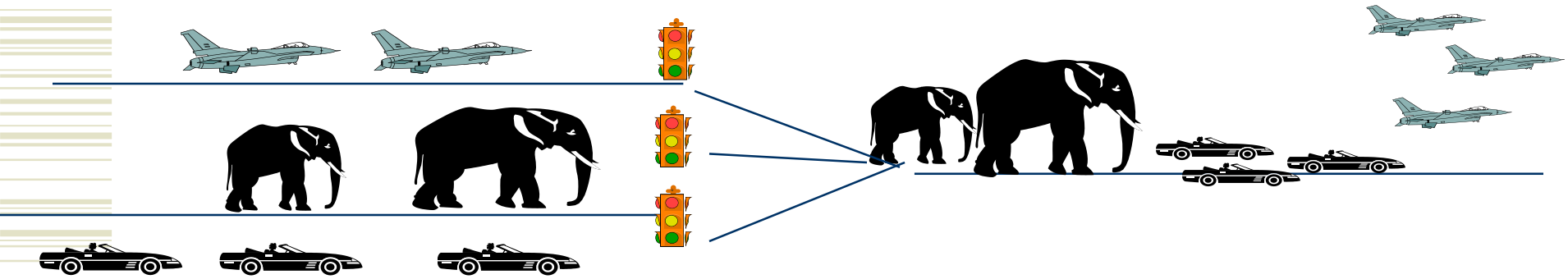


process	time
P_1	6
P_2	3
P_3	1
P_4	7

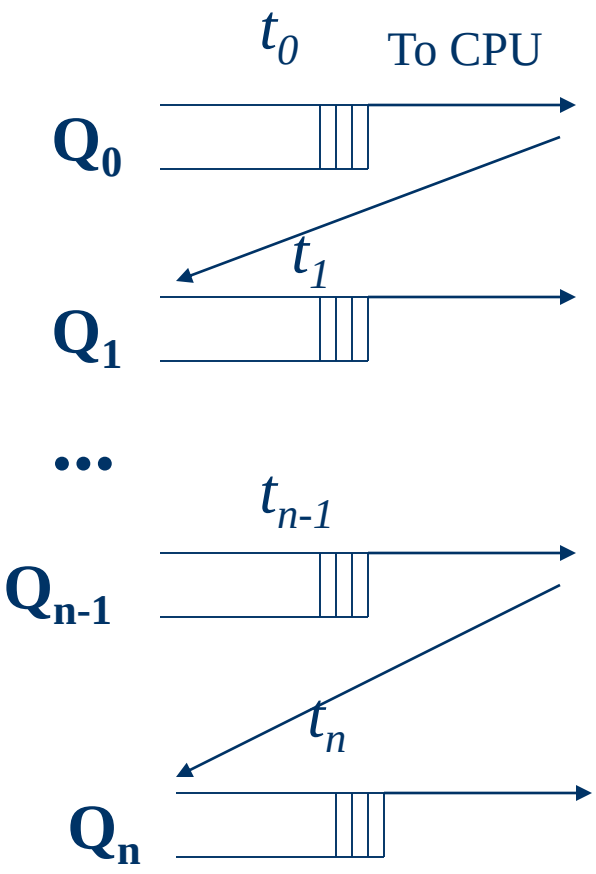
Multilevel Queue Scheduling

- 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



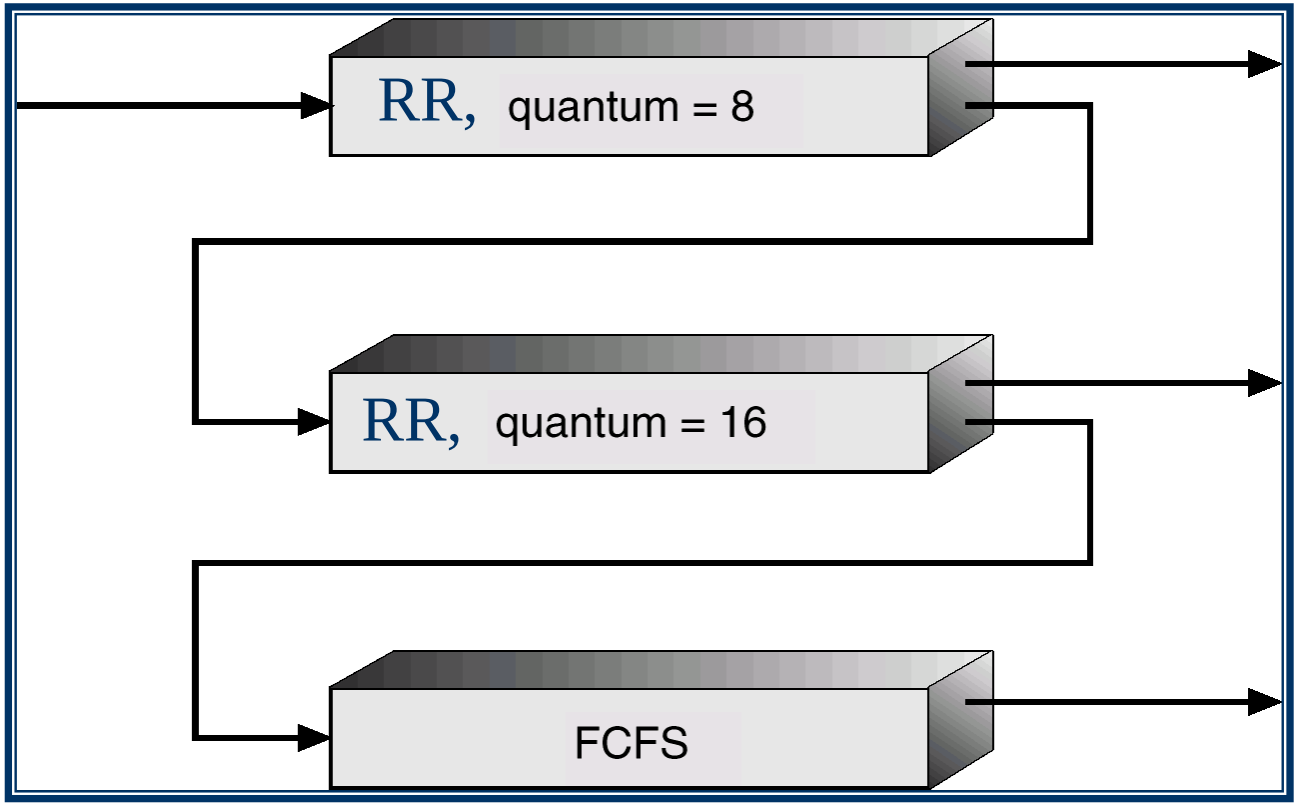
Multilevel Feedback Queue Scheduling—a variation of aging



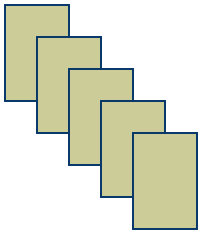
Processes in Q_i have a higher priority than those in Q_{i+1} . Until Q_i is empty, Q_{i+1} can not execute. But once a process has used its time slice, t_i, it is moved into Q_{i+1} instead of back to Q_i, and, of course, $t_i < t_{i+1}$.

An Example

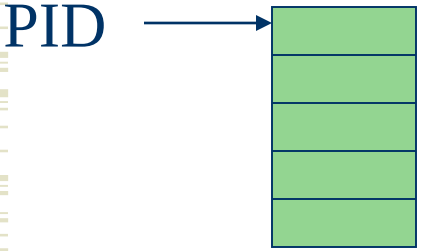
After the Book



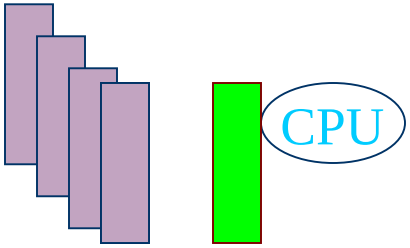
Attachment Simulation (for HW #3): *Common Data Structures*



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.)*

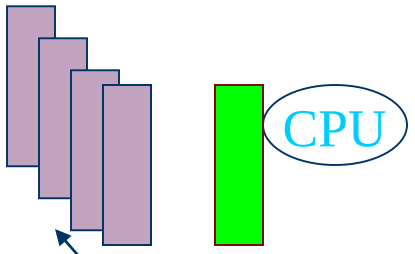
- Two types of events: process *arrival* and process *completion*:

```
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;
            ...
          }
```

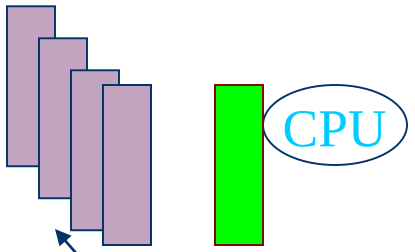


Sorted by completion times

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;
           ...
    }
```