Chapter 6: CPU Scheduling
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- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Multiple-Processor Scheduling
- Real-Time CPU Scheduling
- Operating Systems Examples
- Algorithm Evaluation
Objectives

- To introduce CPU scheduling, which is the basis for multiprogrammed operating systems
- To describe various CPU-scheduling algorithms
- To discuss evaluation criteria for selecting a CPU-scheduling algorithm for a particular system
- To examine the scheduling algorithms of several operating systems
Maximum CPU utilization obtained with multiprogramming

CPU–I/O Burst Cycle – Process execution consists of a cycle of CPU execution and I/O wait

CPU burst followed by I/O burst

CPU burst distribution is of main concern
CPU Scheduler

- **Short-term scheduler** selects from among the processes in ready queue, and allocates the CPU to one of them
  - Queue may be ordered in various ways
- CPU scheduling decisions may take place when a process:
  1. Switches from running to waiting state
  2. Switches from running to ready state
  3. Switches from waiting to ready
  4. Terminates
- Scheduling under 1 and 4 is **nonpreemptive**
- All other scheduling is **preemptive**
Dispatcher

- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
  - switching context
  - switching to user mode
  - jumping to the proper location in the user program to restart that program
- **Dispatch latency** – time it takes for the dispatcher to stop one process and start another running
Scheduling Criteria

- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – # of processes that complete their execution per time unit
- **Turnaround time** – amount of time to execute a particular process
- **Waiting time** – amount of time a process has been waiting in the ready queue
- **Response time** – amount of time it takes from when a request was submitted until the first response is produced, not output (for time-sharing environment)
Scheduling Algorithm Optimization Criteria

- Max CPU utilization
- Max throughput
- Min turnaround time
- Min waiting time
- Min response time
**First- Come, First-Served (FCFS) Scheduling**

<table>
<thead>
<tr>
<th>Process</th>
<th>Burst Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>24</td>
</tr>
<tr>
<td>$P_2$</td>
<td>3</td>
</tr>
<tr>
<td>$P_3$</td>
<td>3</td>
</tr>
</tbody>
</table>

Suppose that the processes arrive in the order: $P_1$, $P_2$, $P_3$

The Gantt Chart for the schedule is:

```
P_1   | P_2 | P_3
0     | 24  | 27  |
```

- Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
- Average waiting time: $(0 + 24 + 27)/3 = 17$
Suppose that the processes arrive in the order: \( P_2, P_3, P_1 \)

- The Gantt chart for the schedule is:

  \[
  \begin{array}{ccc}
  P_2 & P_3 & P_1 \\
  0 & 3 & 6 & 30
  \end{array}
  \]

- Waiting time for \( P_1 = 6; P_2 = 0; P_3 = 3 \)
- Average waiting time: \( (6 + 0 + 3)/3 = 3 \)
- Much better than previous case
- **Convoy effect** - short process behind long process
  - Consider one CPU-bound and many I/O-bound processes
Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its next CPU burst
  - Use these lengths to schedule the process with the shortest time
- SJF is optimal – gives minimum average waiting time for a given set of processes
  - The difficulty is knowing the length of the next CPU request
  - Could ask the user
Example of SJF

<table>
<thead>
<tr>
<th>Process</th>
<th>Burst Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>6</td>
</tr>
<tr>
<td>$P_2$</td>
<td>8</td>
</tr>
<tr>
<td>$P_3$</td>
<td>7</td>
</tr>
<tr>
<td>$P_4$</td>
<td>3</td>
</tr>
</tbody>
</table>

- SJF scheduling chart

- Average waiting time $= \frac{(3 + 16 + 9 + 0)}{4} = 7$
Determining Length of Next CPU Burst

- Can only estimate the length – should be similar to the previous one
  - Then pick process with shortest predicted next CPU burst

- Can be done by using the length of previous CPU bursts, using exponential averaging

  1. \( t_n \) = actual length of \( n^{th} \) CPU burst
  2. \( \tau_{n+1} \) = predicted value for the next CPU burst
  3. \( \alpha, 0 \leq \alpha \leq 1 \)
  4. Define: \( \tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n \).

- Commonly, \( \alpha \) set to \( \frac{1}{2} \)
- Preemptive version called **shortest-remaining-time-first**
Prediction of the Length of the Next CPU Burst

CPU burst ($t_i$)  6  4  6  4  13  13  13  ...  
"guess" ($\tau_i$)  10  8  6  6  5  9  11  12  ...
Examples of Exponential Averaging

- \( \alpha = 0 \)
  - \( \tau_{n+1} = \tau_n \)
  - Recent history does not count

- \( \alpha = 1 \)
  - \( \tau_{n+1} = \alpha t_n \)
  - Only the actual last CPU burst counts

- If we expand the formula, we get:
  \[
  \tau_{n+1} = \alpha t_n + (1 - \alpha)\alpha t_{n-1} + \ldots \\
  + (1 - \alpha)j \alpha t_{n-j} + \ldots \\
  + (1 - \alpha)^{n+1} \tau_0 
  \]

- Since both \( \alpha \) and \( 1 - \alpha \) are less than or equal to 1, each successive term has less weight than its predecessor
Now we add the concepts of varying arrival times and preemption to the analysis.

<table>
<thead>
<tr>
<th>Process</th>
<th>Arrival Time</th>
<th>Burst Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>$P_2$</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>$P_3$</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>$P_4$</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

**Preemptive SJF Gantt Chart**

Average waiting time = \([(10-1)+(1-1)+(17-2)+5-3)]/4 = 26/4 = 6.5 msec
Priority Scheduling

- A priority number (integer) is associated with each process.
- The CPU is allocated to the process with the highest priority (smallest integer \(\equiv\) highest priority):
  - Preemptive
  - Nonpreemptive
- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time.
- Problem \(\equiv\) Starvation – low priority processes may never execute.
- Solution \(\equiv\) Aging – as time progresses increase the priority of the process.
**Example of Priority Scheduling**

<table>
<thead>
<tr>
<th>Process</th>
<th>Burst Time</th>
<th>Priority</th>
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<tbody>
<tr>
<td>$P_1$</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>$P_2$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$P_3$</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$P_4$</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>$P_5$</td>
<td>5</td>
<td>2</td>
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- Priority scheduling Gantt Chart

- Average waiting time = 8.2 msec
Round Robin (RR)

- Each process gets a small unit of CPU time (time quantum \( q \)), usually 10-100 milliseconds. After this time has elapsed, the process is preempted and added to the end of the ready queue.
- If there are \( n \) processes in the ready queue and the time quantum is \( q \), then each process gets \( 1/n \) of the CPU time in chunks of at most \( q \) time units at once. No process waits more than \((n-1)q\) time units.
- Timer interrupts every quantum to schedule next process
- Performance
  - \( q \) large \( \Rightarrow \) FIFO
  - \( q \) small \( \Rightarrow q \) must be large with respect to context switch, otherwise overhead is too high
Example of RR with Time Quantum = 4

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</tr>
</tbody>
</table>

The Gantt chart is:

```
0  4  7  10  14  18  22  26  30
P_1 P_2 P_3 P_1 P_1 P_1 P_1 P_1
```

- Typically, higher average turnaround than SJF, but better *response*
- q should be large compared to context switch time
- q usually 10ms to 100ms, context switch < 10 usec
Time Quantum and Context Switch Time

- Process time = 10
- Quantum: 12
- Context switches: 0
- Quantum: 6
- Context switches: 1
- Quantum: 1
- Context switches: 9
Turnaround Time Varies With The Time Quantum

80% of CPU bursts should be shorter than $q$
Multilevel Queue

- Ready queue is partitioned into separate queues, eg:
  - **foreground** (interactive)
  - **background** (batch)
- Process permanently in a given queue
- Each queue has its own scheduling algorithm:
  - foreground – RR
  - background – FCFS
- Scheduling must be done between the queues:
  - Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation.
  - Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes; i.e., 80% to foreground in RR
  - 20% to background in FCFS
Multilevel Queue Scheduling

highest priority

- system processes

- interactive processes

- interactive editing processes

- batch processes

- student processes

lowest priority
Multilevel Feedback Queue

- A process can move between the various queues; aging can be implemented this way.
- Multilevel-feedback-queue scheduler defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method used to determine when to upgrade a process
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when that process needs service
Example of Multilevel Feedback Queue

Three queues:
- \( Q_0 \) – RR with time quantum 8 milliseconds
- \( Q_1 \) – RR time quantum 16 milliseconds
- \( Q_2 \) – FCFS

Scheduling
- A new job enters queue \( Q_0 \) which is served FCFS
  - When it gains CPU, job receives 8 milliseconds
  - If it does not finish in 8 milliseconds, job is moved to queue \( Q_1 \)
- At \( Q_1 \) job is again served FCFS and receives 16 additional milliseconds
  - If it still does not complete, it is preempted and moved to queue \( Q_2 \)