Basic Concepts

- 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 distribution
Alternating Sequence of CPU and I/O Bursts

Histogram of CPU-burst Times
CPU 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**
  - Consider access to shared data
  - Consider preemption while in kernel mode
  - Consider interrupts occurring during crucial OS activities

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:

- Waiting time for $P_1 = 0$; $P_2 = 24$; $P_3 = 27$
- Average waiting time: $(0 + 24 + 27)/3 = 17$

FCFS Scheduling (Cont.)

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

- The Gantt chart for the schedule is:

- 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>Arrival Time</th>
<th>Burst Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>0.0</td>
<td>6</td>
</tr>
<tr>
<td>$P_2$</td>
<td>2.0</td>
<td>8</td>
</tr>
<tr>
<td>$P_3$</td>
<td>4.0</td>
<td>7</td>
</tr>
<tr>
<td>$P_4$</td>
<td>5.0</td>
<td>3</td>
</tr>
</tbody>
</table>

- SJF scheduling chart

- Average waiting time = $(3 + 16 + 9 + 0) / 4 = 7$
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:
   \[ \tau_{n+1} = \alpha \cdot t_n + (1 - \alpha) \cdot \tau_n. \]

• Commonly, \( \alpha \) set to \( \frac{1}{2} \)
• Preemptive version called **shortest-remaining-time-first**

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Prediction of the Length of the Next CPU Burst

![Graph showing prediction of CPU burst lengths over time](image)

- CPU burst \( (t) \): 6, 4, 6, 4, 13, 13, 13, ...
- "guess" \( (\tau) \): 10, 8, 6, 6, 5, 9, 11, 12, ...

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Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer = highest priority)
  - Preemptive
  - Nonpreemptive
- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time
- Problem = **Starvation** – low priority processes may never execute
- Solution = **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>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>

- Priority scheduling Gantt Chart

```
P_2 | P_5 | P_1 | P_3 | P_4 |
0   | 1   | 6   | 16  | 18  | 19
```

- 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

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**Example of RR with Time Quantum = 4**

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<td>3</td>
</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

Turnaround Time Varies With The Time Quantum

Rule of Thumb:
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

- MQ requires process to be assigned a priori

- 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 $Q_2$
Thread Scheduling

- Distinction between user-level and kernel-level threads

- When threads supported, threads scheduled, not processes

- Many-to-one and many-to-many models, thread library schedules user-level threads to run on LWP
  - Known as **process-contention scope (PCS)** since scheduling competition is within the process
  - Typically done via priority set by programmer

- Kernel thread scheduled onto available CPU is **system-contention scope (SCS)** – competition among all threads in system
Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- **Homogeneous processors** within a multiprocessor
- **Asymmetric multiprocessing** – only one processor accesses the system data structures, alleviating the need for data sharing
- **Symmetric multiprocessing (SMP)** – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
  - Currently, most common
- **Processor affinity** – process has affinity for processor on which it is currently running
  - **soft affinity**
  - **hard affinity**
  - Variations including **processor sets**

NUMA and CPU Scheduling

Note that memory-placement algorithms can also consider affinity.
Multicore Processors

- Recent trend to place multiple processor cores on same physical chip
- Faster and consumes less power
- Multiple threads per core also growing
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens
- Hyperthreading is an example

Multithreaded Multicore System
Virtualization and Scheduling

- Virtualization software schedules multiple guests onto CPU(s)

- Each guest doing its own scheduling
  - Not knowing it doesn’t own the CPUs
  - Can result in poor response time
  - Can effect time-of-day clocks in guests

- Can undo good scheduling algorithm efforts of guests