Context Switching

- Processes are managed by a shared chunk of OS code called the kernel
  - Important: the kernel is not a separate process, but rather runs as part of some user process
- Control flow passes from one process to another via a context switch.

Thread Scheduling: Transferring Context Blocks

Coroutines
transfer(other)
  - save all callee-saves registers on stack, including ra and fp
  - *current := sp
  - current := other
  - sp := *current
  - pop all callee-saves registers (including ra, but NOT sp!)
  - return (into different coroutine!)

Uniprocessor Scheduling

- Use Ready List to reschedule voluntarily (cooperative threading)
  - reschedule:
    - t : cb := dequeue(ready_list)
    - transfer(t)
  - yield:
    - enqueue(ready_list, current)
    - reschedule
  - sleep_on(q):
    - enqueue(q, current)
    - reschedule
Preemption

- Use timer interrupts or signals to trigger involuntary yields
- Protect scheduler data structures by disabling/re-enabling prior to/after rescheduling

yield:
  disable_signals
  enqueue(ready_list, current)
  reschedule
  re-enable_signals

Process State

- As a process executes, it changes state:
  - new: The process is being created
  - ready: The process is waiting to be assigned to a process
  - running: Instructions are being executed
  - waiting: The process is waiting for some event to occur
  - terminated: The process has finished execution

Queues for PCBs

- Ready queue - set of all processes ready for execution.
- Device queues - set of processes waiting for an I/O device.
- Process migration between the various queues.

CPU Switch From Process to Process

When can the OS switch the CPU from one process to another?

Which one to switch to? - scheduling
CPU Scheduling

- Selects from among the processes/threads that are ready to execute, and allocates the CPU to it
- CPU scheduling may take place at:
  1. Hardware interrupt/software exception
  2. System calls
- Nonpreemptive:
  - Scheduling only when the current process terminates or not able to run further
- Preemptive:
  - Scheduling can occur at any opportunity possible

Scheduling Criteria

- Minimize turnaround time - amount of time to execute a particular process
- Maximize throughput - # of processes that complete their execution per time unit
- Maximize CPU utilization - the proportion of the CPU that is not idle
- Minimize response time - amount of time it takes from when a request was submitted until the first response is produced (interactivity)
- Fairness: avoid starvation

First-Come, First-Served (FCFS) Scheduling

<table>
<thead>
<tr>
<th>Process</th>
<th>CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>24</td>
</tr>
<tr>
<td>P₂</td>
<td>3</td>
</tr>
<tr>
<td>P₃</td>
<td>3</td>
</tr>
</tbody>
</table>

- Suppose that the processes arrive in the order: P₁, P₂, P₃
  The schedule is:

```
       P₁   P₂   P₃
       0  24  27  30
```

- Turnaround time for P₁ = 24; P₂ = 27; P₃ = 30
- Average turnaround time: (24 + 27 + 30)/3 = 27

FCFS Scheduling (Cont.)

Suppose that the processes arrive in the order P₂, P₃, P₁.

- The schedule is:

```
     P₂  P₃  P₁
     0   3   6  30
```

- Turnaround time for P₁ = 30; P₂ = 3; P₃ = 6
- Average turnaround time: (30 + 3 + 6)/3 = 13
- Much better than previous case.
- Short process delayed by long process: Convoy effect
Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its CPU time. Use these lengths to schedule the process with the shortest CPU time.
- Two variations:
  - Non-preemptive - once CPU given to the process it cannot be taken away until it completes
  - Preemptive - if a new process arrives with CPU time less than remaining time of current executing process, preempt
- Preemptive SJF is optimal - gives minimum average turnaround time for a given set of processes
- Problem:
  - don’t know the process CPU time ahead of time

Example of Preemptive SJF

<table>
<thead>
<tr>
<th>Process</th>
<th>Arrival Time</th>
<th>CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>0.0</td>
<td>7</td>
</tr>
<tr>
<td>P₂</td>
<td>2.0</td>
<td>4</td>
</tr>
<tr>
<td>P₃</td>
<td>4.0</td>
<td>1</td>
</tr>
<tr>
<td>P₄</td>
<td>5.0</td>
<td>4</td>
</tr>
</tbody>
</table>

SJF (preemptive)

Average turnaround time = \((16 + 5 + 1 + 6)/4\) = 7

Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority
  - preemptive
  - nonpreemptive
- SJF is a priority scheduling where priority is the predicted CPU time
- Problem: Starvation - low priority processes may never execute
- Solution: Aging - as time progresses, increase the priority of the process

Round Robin (RR)

- Each process gets a fixed unit of CPU time (time quantum), 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
- Performance
  - \(q\) small \(\Rightarrow\) fair, starvation-free, better interactivity
  - \(q\) large \(\Rightarrow\) FIFO
  - \(q\) must be large with respect to context switch cost, otherwise overhead is too high
Cost of Context Switch

- Direct overhead of context switch
  - saving old contexts, restoring new contexts, ... ...

- Indirect overhead of context switch
  - caching, memory management overhead

Example of RR with Quantum = 20

<table>
<thead>
<tr>
<th>Process</th>
<th>CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_1</td>
<td>53</td>
</tr>
<tr>
<td>P_2</td>
<td>17</td>
</tr>
<tr>
<td>P_3</td>
<td>68</td>
</tr>
<tr>
<td>P_4</td>
<td>24</td>
</tr>
</tbody>
</table>

- The schedule is:

<table>
<thead>
<tr>
<th>P_1</th>
<th>P_2</th>
<th>P_3</th>
<th>P_4</th>
<th>P_1</th>
<th>P_3</th>
<th>P_3</th>
<th>P_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
<td>37</td>
<td>57</td>
<td>77</td>
<td>97</td>
<td>117</td>
<td>121</td>
</tr>
</tbody>
</table>

- Typically, higher average turnaround than SJF, but better response

Multilevel Scheduling

- Ready tasks are partitioned into separate classes:
  - foreground (interactive)
  - background (batch)

- Each class has its own scheduling algorithm,
  - foreground - RR
  - background - FCFS

- Scheduling must be done between the classes.
  - Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation
  - Time slice - each class gets a certain amount of CPU time which it can schedule amongst its processes; e.g.,
    - 80% to foreground in RR
    - 20% to background in FCFS

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 $Q_2$.

Multilevel Feedback Queues

Lottery Scheduling

- Give processes lottery tickets for various system resources
- Choose ticket at random and allow process holding the ticket to get the resource
- Hold a lottery at periodic intervals
- Properties
  - Chance of winning proportional to number of tickets held (highly responsive)
  - Cooperating processes may exchange tickets
  - Fair-share scheduling easily implemented by allocating tickets to users and dividing tickets among child processes

Real-Time Scheduling

- **Hard real-time systems** – required to complete a critical task within a guaranteed amount of time
- **Soft real-time computing** – requires that critical processes receive priority over less fortunate ones
- EDF – Earliest Deadline First Scheduling
Linux Task Scheduling

- Linux 2.5 and up uses a preemptive, priority-based algorithm with two separate priority ranges:
  - A time-sharing class/range for fair preemptive scheduling (nice value ranging from 100-140)
  - A real-time class that conforms to POSIX real-time standard (0-99)
- Numerically lower values indicate higher priority
- Higher-priority tasks get longer time quanta (200-10 ms)
- One runqueue per processor (logical or physical); load balancing phase to equally distribute tasks among runqueues
- Runqueue indexed by priority and contains two priority arrays - active and expired
- Choose task with highest priority on active array; switch active and expired arrays when active is empty
- Time-sharing tasks are assigned the nice value +/- 5

CPU Scheduling on Multi-Processors

- Cache affinity
  - keep a task on a particular processor as much as possible
- Resource contention
  - prevent resource-conflicting tasks from running simultaneously on sibling processors

Multiprocessor Scheduling

- Timesharing
  - similar to uni-processor scheduling - one queue of ready tasks (protected by synchronization), a task is dequeued and executed when a processor is available
- Space sharing
- cache affinity
  - affinity-based scheduling - try to run each process on the processor that it last ran on
- caching sharing and synchronization of parallel/concurrent applications
  - gang/cohort scheduling - utilize all CPUs for one parallel/concurrent application at a time

Anderson et al. 1989 (IEEE TOCS)

- Raises issues of
  - Locality (per-processor data structures)
  - Granularity of scheduling tasks
  - Lock overhead
  - Tradeoff between throughput and latency
    - Large critical sections are good for best-case latency (low locking overhead) but bad for throughput (low parallelism)
Performance Measures

- Latency
  - Cost of thread management under the best case assumption of no contention for locks
- Throughput
  - Rate at which threads can be created, started, and finished when there is contention

Optimizations

- Allocate stacks lazily
- Store deallocated control blocks and stacks in free lists
- Create per-processor ready lists
- Create local free lists for locality
- Queue of idle processors (in addition to queue of waiting threads)

Ready List Management

- Single lock for all data structures
- Multiple locks, one per data structure
- Local freelists for control blocks and stacks, single shared locked ready list
- Queue of idle processors with preallocated control block and stack waiting for work
- Local ready list per processor, each with its own lock

Solaris Dispatch Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>Time Quantum</th>
<th>Time Quantum Expired</th>
<th>Return from Sleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>160</td>
<td>0</td>
<td>51</td>
</tr>
<tr>
<td>15</td>
<td>160</td>
<td>5</td>
<td>51</td>
</tr>
<tr>
<td>20</td>
<td>120</td>
<td>10</td>
<td>52</td>
</tr>
<tr>
<td>25</td>
<td>120</td>
<td>15</td>
<td>52</td>
</tr>
<tr>
<td>30</td>
<td>80</td>
<td>20</td>
<td>53</td>
</tr>
<tr>
<td>35</td>
<td>80</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
<td>40</td>
<td>40</td>
<td>30</td>
<td>55</td>
</tr>
<tr>
<td>45</td>
<td>40</td>
<td>35</td>
<td>56</td>
</tr>
<tr>
<td>50</td>
<td>40</td>
<td>40</td>
<td>58</td>
</tr>
<tr>
<td>55</td>
<td>40</td>
<td>45</td>
<td>58</td>
</tr>
<tr>
<td>59</td>
<td>20</td>
<td>49</td>
<td>59</td>
</tr>
</tbody>
</table>
Solaris Scheduling

Multiprocessor Scheduling in Linux 2.6
- One ready task queue per processor
  - scheduling within a processor and its ready task queue is similar to single-processor scheduling
- One task tends to stay in one queue
  - for cache affinity
- Tasks move around when load is unbalanced
  - e.g., when the length of one queue is less than one quarter of the other
  - which one to pick?
- No native support for gang/cohort scheduling or resource-contention-aware scheduling

Linux Scheduling
- Constant order $O(1)$ scheduling time
- Two priority ranges: time-sharing and real-time
- Real-time range from 0 to 99 and nice value from 100 to 140

Priorities and Time-slice length
<table>
<thead>
<tr>
<th>numeric priority</th>
<th>relative priority</th>
<th>time quantum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>highest</td>
<td>real-time tasks</td>
</tr>
<tr>
<td>99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>other tasks</td>
</tr>
<tr>
<td>140</td>
<td>lowest</td>
<td></td>
</tr>
</tbody>
</table>
List of Tasks Indexed According to Priorities

<table>
<thead>
<tr>
<th>active array</th>
<th>expired array</th>
</tr>
</thead>
<tbody>
<tr>
<td>priority</td>
<td>priority</td>
</tr>
<tr>
<td>[0]</td>
<td>[0]</td>
</tr>
<tr>
<td>[1]</td>
<td>[1]</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Resource Contention-Aware Scheduling I

- Hardware resource sharing/contention in multi-processors
  - SMP processors share memory bus bandwidths
  - Multi-core processors share L2 cache
  - SMT processors share a lot more stuff
- An example: on an SMP machine
  - a web server benchmark delivers around 6300 reqs/sec on one processor, but only around 9500 reqs/sec on an SMP with 4 processors
- Contention-reduction scheduling
  - co-scheduling tasks with complementary resource needs (a computation-heavy task and a memory access-heavy task)
  - In [Fedorova et al. USENIX2005], IPC is used to distinguish computation-heavy tasks from memory access-heavy tasks

Resource Contention-Aware Scheduling II

- What if contention on a resource is unavoidable?
- Two evils of contention
  - high contention ⇒ performance slowdown
  - fluctuating contention ⇒ uneven application progress over the same amount of time ⇒ poor fairness
- [Zhang et al. HotOS2007] Scheduling so that:
  - very high contention is avoided
  - the resource contention is kept stable
Disclaimer

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