In discussing process management and synchronization, we talked about context switching among processes/threads on the ready queue. But we have glossed over the details of exactly which thread is chosen from the ready queue. Making this decision is called scheduling. In this lecture, we’ll look at:

- The goals of scheduling
- Starvation
- Various well-known scheduling algorithms
- Standard Unix scheduling algorithm
Multiprogramming

- In a multiprogramming system, we try to increase CPU utilization and job throughput by overlapping I/O and CPU activities
  - Doing this requires a combination of mechanisms and policy
- We have covered the mechanisms
  - Context switching, how and when it happens
  - Process queues and process states
- Now we’ll look at the policies
  - Which process (thread) to run, for how long, etc.
- We’ll refer to schedulable entities as jobs (standard usage) – could be processes, threads, people, etc.

Scheduling Goals

- Scheduling works at two levels in an operating system
  - To determine the multiprogramming level – the number of jobs loaded into primary memory
    » Moving jobs to/from memory is often called swapping
  - To decide what job to run next to guarantee “good service”
    » Good service could be one of many different criteria
- These decisions are known as long-term and short-term scheduling decisions, respectively
  - Long-term scheduling happens relatively infrequently
    » Significant overhead in swapping a process out to disk
  - Short-term scheduling happens relatively frequently
    » Want to minimize the overhead of scheduling
      ■ Fast context switches, fast queue manipulation
The scheduler (aka dispatcher) is the module that manipulates
the queues, moving jobs to and fro.

The scheduling algorithm determines which jobs are chosen to
run next and what queues they wait on.

In general, the scheduler runs:
- When a job switches from running to waiting
- When an interrupt occurs
- When a job is created or terminated

We’ll discuss scheduling algorithms in two contexts:
- In preemptive systems the scheduler can interrupt a running job
  (involuntary context switch)
- In non-preemptive systems, the scheduler waits for a running job to
  explicitly block (voluntary context switch)

Scheduling algorithms can have many different goals:
- CPU utilization
- Job throughput (# jobs/unit time)
- Turnaround time \( T_{\text{finish}} - T_{\text{start}} \)
- Waiting time \( \text{Avg}(T_{\text{wait}}) \): avg time spent on wait queues
- Response time \( \text{Avg}(T_{\text{ready}}) \): avg time spent on ready queue

Batch systems
- Strive for job throughput, turnaround time (supercomputers)

Interactive systems
- Strive to minimize response time for interactive jobs (PC)
Starvation

Starvation is a scheduling “non-goal”:

- **Starvation** is a situation where a process is prevented from making progress because some other process has the resource it requires
  - Resource could be the CPU, or a lock (recall readers/writers)
- **Starvation usually a side effect of the sched. algorithm**
  - A high priority process always prevents a low priority process from running on the CPU
  - One thread always beats another when acquiring a lock
- **Starvation can be a side effect of synchronization**
  - Constant supply of readers always blocks out writers

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FCFS/FIFO

- First-come first-served (FCFS), first-in first-out (FIFO)
  - Jobs are scheduled in order of arrival to ready Q
  - “Real-world” scheduling of people in lines (e.g., supermarket)
  - Typically non-preemptive (no context switching at market)
  - Jobs treated equally, no starvation
- **Problem**
  - Average waiting time can be large if small jobs wait behind long ones (high turnaround time)
    - You have a basket, but you’re stuck behind someone with a cart
Shortest Job First (SJF)

- Shortest Job First (SJF)
  - Choose the job with the smallest expected CPU burst
    » Person with smallest number of items to buy
  - Provably optimal minimum average waiting time
- Problem
  - Impossible to know size of CPU burst
    » Like choosing person in line without looking inside basket/cart
  - How can you make a reasonable guess?
  - Can potentially starve
- Flavors
  - Can be either preemptive or non-preemptive
  - Preemptive SJF is called shortest remaining time first (SRTF)

Priority Scheduling

- Priority Scheduling
  - Choose next job based on priority
    » Airline checkin for first class passengers
  - Can implement SJF, priority = 1/(expected CPU burst)
  - Also can be either preemptive or non-preemptive
  - This is what you’re implementing in Nachos in Project 1
- Problem
  - Starvation – low priority jobs can wait indefinitely
- Solution
  - “Age” processes
    » Increase priority as a function of waiting time
    » Decrease priority as a function of CPU consumption
**Round Robin (RR)**

- Round Robin
  - Excellent for timesharing
  - Ready queue is treated as a circular queue (FIFO)
  - Each job is given a time slice called a **quantum**
  - A job executes for the duration of the quantum, or until it blocks or is interrupted
  - No starvation
  - Can be preemptive or non-preemptive

- **Problem**
  - Context switches are frequent and need to be very fast

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**Combining Algorithms**

- Scheduling algorithms can be combined
  - Have multiple queues
  - Use a different algorithm for each queue
  - Move processes among queues

- **Example: Multiple-level feedback queues (MLFQ)**
  - Multiple queues representing different job types
    - Interactive, CPU-bound, batch, system, etc.
  - Queues have priorities, jobs on same queue scheduled RR
  - Jobs can move among queues based upon execution history
    - Feedback: Switch from interactive to CPU-bound behavior
Unix Scheduler

- The canonical Unix scheduler uses a MLFQ
  - 3-4 classes spanning ~170 priority levels
    - Timesharing: first 60 priorities
    - System: next 40 priorities
    - Real-time: next 60 priorities
    - Interrupt: next 10 (Solaris)
- Priority scheduling across queues, RR within a queue
  - The process with the highest priority always runs
  - Processes with the same priority are scheduled RR
- Processes dynamically change priority
  - Increases over time if process blocks before end of quantum
  - Decreases over time if process uses entire quantum

Motivation of Unix Scheduler

- The idea behind the Unix scheduler is to reward interactive processes over CPU hogs
- Interactive processes (shell, editor, etc.) typically run using short CPU bursts
  - They do not finish quantum before waiting for more input
- Want to minimize response time
  - Time from keystroke (putting process on ready queue) to executing keystroke handler (process running)
  - Don’t want editor to wait until CPU hog finishes quantum
- This policy delays execution of CPU-bound jobs
  - But that’s ok
Scheduling Summary

- Scheduler (dispatcher) is the module that gets invoked when a context switch needs to happen
- Scheduling algorithm determines which process runs, where processes are placed on queues
- Many potential goals of scheduling algorithms
  - Utilization, throughput, wait time, response time, etc.
- Various algorithms to meet these goals
  - FCFS/FIFO, SJF, Priority, RR
- Can combine algorithms
  - Multiple-level feedback queues
  - Unix example

Deadlock

- Synchronization is a live gun – we can easily shoot ourselves in the foot
  - Incorrect use of synchronization can block all processes
  - You have likely been intuitively avoiding this situation already
- More generally, processes that allocate multiple resources generate dependencies on those resources
  - Locks, semaphores, monitors, etc., just represent the resources that they protect
- If one process tries to allocate a resource that a second process holds, and vice-versa, they can never make progress
- We call this situation deadlock, and we’ll look at:
  - Definition and conditions necessary for deadlock
  - Representation of deadlock conditions
  - Approaches to dealing with deadlock
Deadlock Definition

- Deadlock is a problem that can arise:
  - When processes compete for access to limited resources
  - When processes are incorrectly synchronized
- Definition:
  - Deadlock exists among a set of processes if every process is waiting for an event that can be caused only by another process in the set.

```c
lockA->Acquire();
...
lockB->Acquire();
```

Process 1

```
lockB->Acquire();
...
lockA->Acquire();
```

Process 2

Conditions for Deadlock

- Specifically, deadlock can exist if and only if the following four conditions hold simultaneously:
  1. Mutual exclusion – At least one process must be held in a non-sharable mode.
  2. Hold and wait – There must be one process holding one resource and waiting for another resource
  3. No preemption – Resources cannot be preempted (critical sections cannot be aborted externally)
  4. Circular wait – There must exist a set of processes \([P_1, P_2, P_3, \ldots, P_n]\) such that \(P_1\) is waiting for \(P_2\), \(P_2\) for \(P_3\), etc.
Resource Allocation Graph

- Deadlock can be described using a resource allocation graph (RAG).
- The RAG consists of a set of vertices $P_1, P_2, \ldots, P_n$ of processes and $R_1, R_2, \ldots, R_m$ of resources.
  - A directed edge from a process to a resource, $P_i \rightarrow R_j$, implies that $P_i$ has requested $R_j$.
  - A directed edge from a resource to a process, $R_i \rightarrow P_i$, implies that $R_i$ has been allocated by $P_i$.
  - Each resource has a fixed number of units.
- If the graph has no cycles, deadlock cannot exist.
- If the graph has a cycle, deadlock may exist.

RAG Example

- A cycle... and deadlock!
- Same cycle... but no deadlock. Why?
Dealing With Deadlock

- There are four approaches for dealing with deadlock:
  - Ignore it – how lucky do you feel?
  - Prevention – make it impossible for deadlock to happen
  - Avoidance – control allocation of resources
  - Detection and Recovery – look for a cycle in dependencies

Deadlock Prevention

- Prevention – Ensure that at least one of the necessary conditions cannot happen
  - Mutual exclusion
    » Make resources sharable (not generally practical)
  - Hold and wait
    » Process cannot hold one resource when requesting another
    » Process requests, releases all needed resources at once
  - Preemption
    » OS can preempt resource (costly)
  - Circular wait
    » Impose an ordering (numbering) on the resources and request them in order (popular implementation technique)
Deadlock Avoidance

- Avoidance
  - Provide information in advance about what resources will be needed by processes to guarantee that deadlock will not happen
  - System only grants resource requests if it knows that the process can obtain all resources it needs in future requests
  - Avoids circularities (wait dependencies)

- Tough
  - Hard to determine all resources needed in advance
  - Good theoretical problem, not as practical to use

Banker’s Algorithm

- The Banker’s Algorithm is the classic approach to deadlock avoidance for resources with multiple units
  1. Assign a credit limit to each customer (process)
     - Maximum credit claim must be stated in advance
  2. Reject any request that leads to a dangerous state
     - A dangerous state is one where a sudden request by any customer for the full credit limit could lead to deadlock
     - A recursive reduction procedure recognizes dangerous states
  3. In practice, the system must keep resource usage well below capacity to maintain a resource surplus
     - Rarely used in practice due to low resource utilization
Detection and Recovery

- Detection and recovery
  - If we don’t have deadlock prevention or avoidance, then deadlock may occur
  - In this case, we need to detect deadlock and recover from it
- To do this, we need two algorithms
  - One to determine whether a deadlock has occurred
  - Another to recover from the deadlock
- Possible, but expensive (time consuming)
  - Implemented in VMS
  - Run detection algorithm when resource request times out

Deadlock Detection

- Detection
  - Traverse the resource graph looking for cycles
  - If a cycle is found, preempt resource (force a process to release)
- Expensive
  - Many processes and resources to traverse
- Only invoke detection algorithm depending on
  - How often or likely deadlock is
  - How many processes are likely to be affected when it occurs
Deadlock Recovery

Once a deadlock is detected, we have two options…

1. Abort processes
   - Abort all deadlocked processes
     » Processes need start over again
   - Abort one process at a time until cycle is eliminated
     » System needs to rerun detection after each abort

2. Preempt resources (force their release)
   - Need to select process and resource to preempt
   - Need to rollback process to previous state
   - Need to prevent starvation

Deadlock Summary

- Deadlock occurs when processes are waiting on each other and cannot make progress
  - Cycles in Resource Allocation Graph (RAG)
- Deadlock requires four conditions
  - Mutual exclusion, hold and wait, no resource preemption, circular wait
- Four approaches to dealing with deadlock:
  - Ignore it – Living life on the edge
  - Prevention – Make one of the four conditions impossible
  - Avoidance – Banker’s Algorithm (control allocation)
  - Detection and Recovery – Look for a cycle, preempt or abort
Next time...

- Read Chapter 4.1, 4.2