CSE 120
Principles of Operating Systems

Spring 2018

Lecture 8: Scheduling and Deadlock

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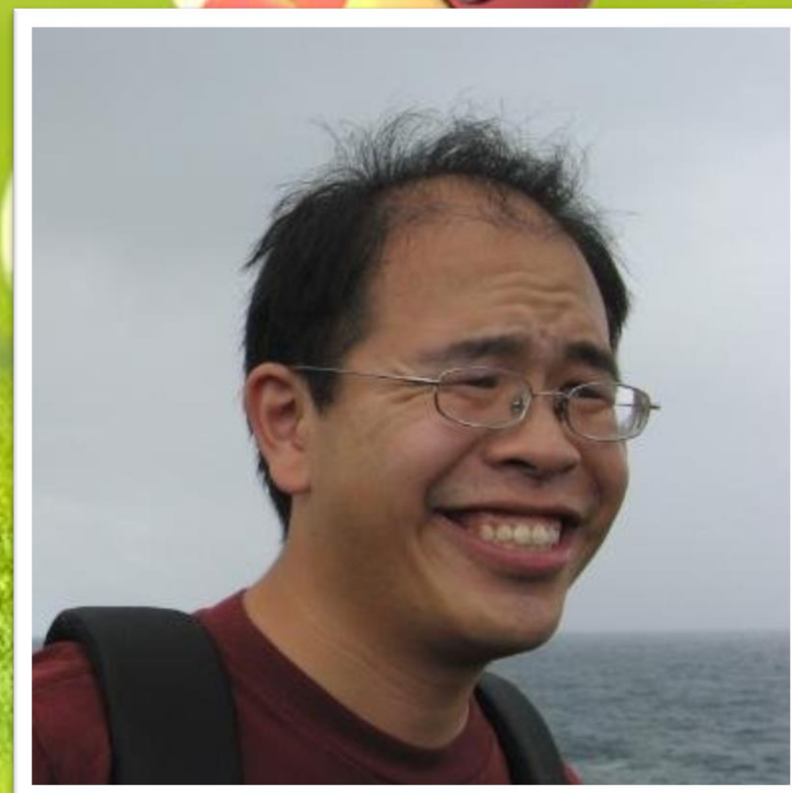
Administrivia

- Friday
  - Project #1 due at 11:59pm
- Saturday
  - Homework #2 due at 11:59pm
  - Will post solutions Sunday morning
- Monday
  - Q&A review session 3pm (more details on Piazza)
- Tuesday
  - Midterm

Edward Wu (UCSD Alumnus)
Director & Technical Lead
Niantic

Tuesday, May 1 @ 9:30am
CSE 1242



Scheduling Overview

- 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:
  - 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 memory
    - Moving jobs to/from memory is 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

Scheduling

- 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 (e.g., I/O completes)
  - 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 Goals

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

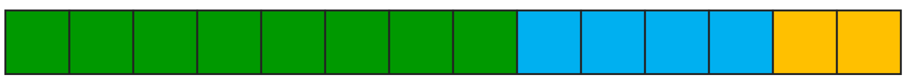
- Starvation is a situation where a process is prevented from making progress because some other process has the resource it requires
  - Resource could be the CPU, or a lock (recall readers/writers)
- Starvation usually a side effect of the sched. algorithm
  - A high priority process always prevents 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

FCFS/FIFO

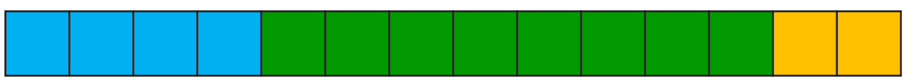
- First-come first-served (FCFS), first-in first-out (FIFO)
  - Jobs are scheduled in order of arrival to ready Q
  - “Real-world” scheduling of people in lines (e.g., supermarket)
  - Typically non-preemptive (no context switching at market)
  - Jobs treated equally, no starvation
- Problem
  - Average 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)

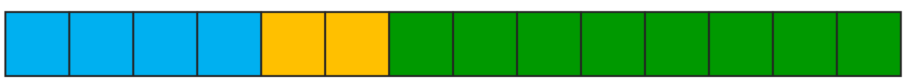
- Shortest Job First (SJF)
  - Choose the job with the smallest expected CPU burst
    - Person with smallest number of items to buy
  - Provably optimal minimum average waiting time (AWT)



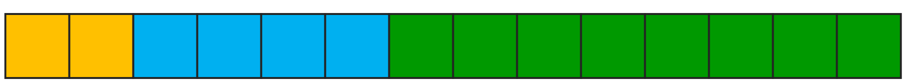
AWT = (8 + (8+4)+(8+4+2))/3 = 11.33



AWT = (4 + (4+8)+(4+8+2))/3 = 10



AWT = (4+ (4+2)+(4+2+8))/3 = 8



AWT = (2 + (2+4)+(2+4+8))/3 = 7.33

Shortest Job First (SJF)

- Problems
  - 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
- 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

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 Overhead

- Operating systems aim to minimize overhead
  - Context switching takes non-zero time, so it is pure overhead
  - Overhead includes context switch + choosing next process
- Modern time-sharing OSes (Unix, Windows, …) time-slice processes in ready list
  - A process runs for its quantum, OS context switches to another, next process runs, etc.
  - A CPU-bound process will use its entire quantum (e.g., 10ms)
  - An IO-bound process will use part (e.g., 1ms), then issue IO
  - The IO-bound process goes on a wait queue, the OS switches to the next process to run, the IO-bound process goes back on the ready list when the IO completes

Utilization

- CPU utilization is the fraction of time the system is doing useful work (e.g., not context switching)
- If the system has
  - Quantum of 10ms + context-switch overhead of 0.1ms
  - 3 CPU-bound processes + round-robin scheduling
- In steady-state, time is spent as follows:
  - 10ms + 0.1ms + 10ms + 0.1ms + 10ms + 0.1ms
  - CPU utilization = time doing useful work / total time
  - CPU utilization = (3*10ms) / (3*10ms + 3*0.1ms) = 30/30.3
- If one process is IO-bound, it will not use full quantum
  - 10ms + 0.1ms + 10ms + 0.1ms + 1ms + 0.1ms
  - CPU util = (2*10 + 1) / (2*10 + 1 + 3*0.1) = 21/21.3

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.

Process 1

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

Process 2

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

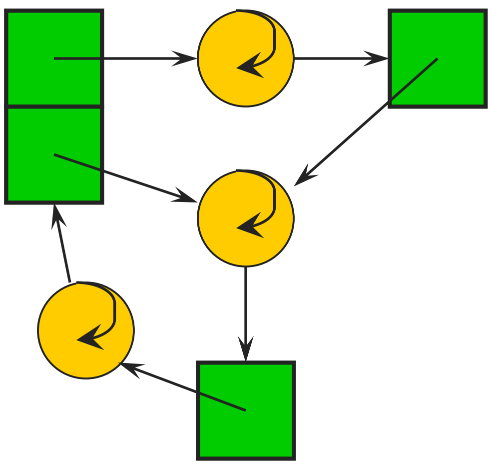
Conditions for Deadlock

- Deadlock can exist if and only if the following four conditions hold simultaneously:
  1. Mutual exclusion – At least one resource 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,…,P_n] such that P_1 is waiting for P_2, P_2 for P_3, etc.

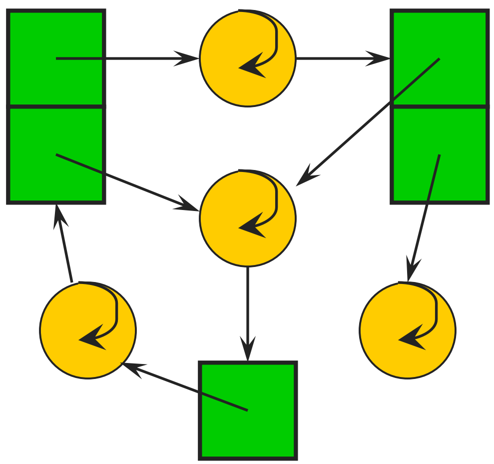
Resource Allocation Graph

- Deadlock can be described using a resource allocation graph (RAG)
- The RAG consists of a set of vertices $P=\{P_1, P_2, \ldots, P_n\}$ of processes and $R=\{R_1, R_2, \ldots, R_m\}$ of resources
  - ♦ A directed edge from a process to a resource, $P_i \rightarrow R_i$, means that P_i has requested R_j
  - ♦ A directed edge from a resource to a process, $R_i \rightarrow P_i$, means that R_j 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?

A Simpler Case

- If all resources are single unit and all processes make single requests, then we can represent the resource state with a simpler waits-for graph (WFG)
  - Useful for tracking locks
- The WFG consists of a set of vertices $P=\{P_1, P_2, \ldots, P_n\}$ of processes
  - A directed edge $P_i \rightarrow P_j$ means that P_i has requested a resource that P_j currently holds
- If the graph has no cycles, deadlock cannot exist
- If the graph has a cycle, deadlock exists

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/claim 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 to 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