

CSE 120

Principles of Operating Systems

Fall 2023

Lecture 8: Scheduling and Deadlock

Geoffrey M. Voelker

Administrivia

- Thursday
 - ◆ Office hours at 2pm, help w/ lab hours 5pm
- Friday
 - ◆ Project #1 due at 11:59pm
- Saturday
 - ◆ Homework #2 due at 11:59pm
- Monday
 - ◆ Q&A review session at 5pm (will post details on piazza)
- Tuesday
 - ◆ Midterm

Scheduling Overview

- With processes, threads, and synchronization, we talked about context switching using 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
 - ◆ Various well-known scheduling algorithms
 - ◆ Standard Unix scheduling algorithm
 - ◆ Deadlock

Multiprogramming

- Multiprogramming systems share CPU resources by time-slicing the CPU
 - ◆ 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.
- Schedulable entities often just called **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 Metrics

- Scheduling algorithms can have many different goals:
 - ◆ CPU utilization (%CPU doing useful work)
 - ◆ Job throughput (# jobs/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

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 turnaround time



$$T = (8 + (8+4) + (8+4+2))/3 = 11.33$$



$$T = (4 + (4+8) + (4+8+2))/3 = 10$$



$$T = (4 + (4+2) + (4+2+8))/3 = 8$$



$$T = (2 + (2+4) + (2+4+8))/3 = 7.33$$

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 boarding for first class passengers
 - ♦ Can implement SJF, $\text{priority} = 1/(\text{expected CPU burst})$
 - ♦ 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
- 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 = $(3 \cdot 10\text{ms}) / (3 \cdot 10\text{ms} + 3 \cdot 0.1\text{ms}) = 30/30.3$
- If one process is IO-bound, it will not use full quantum
 - ♦ 10ms + 0.1ms + 10ms + 0.1ms + 1ms + 0.1ms
 - ♦ CPU util = $(2 \cdot 10 + 1) / (2 \cdot 10 + 1 + 3 \cdot 0.1) = 21/21.3$

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 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.

Thread 1

```
lockA.acquire();  
...  
lockB.acquire();
```

→

Thread 2

```
lockB.acquire();  
...  
lockA.acquire();
```

→

Deadlock with Join

Thread A

```
...  
B.join();  
...
```

Thread B

```
...  
A.join();  
...
```

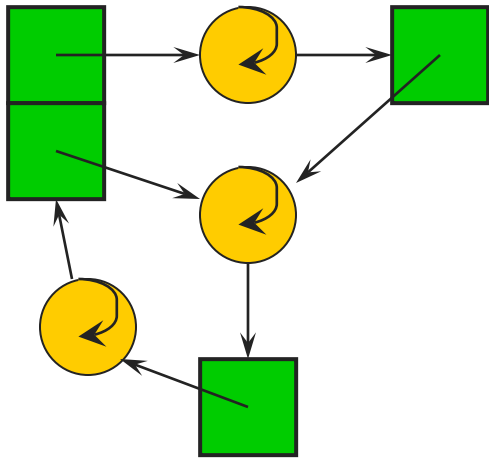
Conditions for Deadlock

- 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 $[P_1, P_2, P_3, \dots, P_n]$ such that P_1 is waiting for P_2 , P_2 for P_3 , etc.

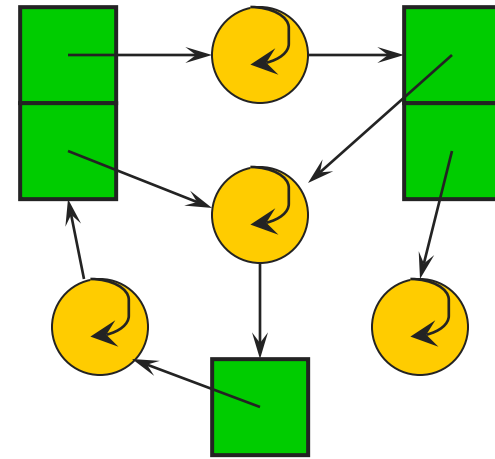
Resource Allocation Graph

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

- Ensure that at least one of the necessary conditions cannot occur
 - ◆ 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 OS implementation technique when using multiple locks**

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
 - ◆ Fine theoretical problem, not as practical to use

Detection and Recovery

- Detection and recovery
 - ♦ If we don't have deadlock prevention or avoidance, then deadlock may occur
 - ♦ In this case, we could 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
 - ♦ Not a feature of current common OSes
 - » If an app wants it, it has to detect and recover itself

Detection and Recovery

- Detection
 - ◆ Traverse the resource graph looking for cycles
- Recovery
 - ◆ Preempt resource (force a process to release)
 - ◆ Abort process (all process resources freed up)
- 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 Summary

- Deadlock occurs when processes are waiting on each other and cannot make progress
 - ◆ Cycles in RAG/WFG
- 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