CSE 120
Principles of Operating Systems

Spring 2023

Lecture 7: Condition Variables and Deadlock

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Administrivia

- Homework #1
  - Solutions on the course webpage
  - Grades on Canvas and Gradescope
- Project 1
  - Ongoing, due 5/2
- Homework #2
  - Ongoing, due 5/2
- Midterm in class on 5/4
  - We will review in class on 5/2
  - Extra office hour 10-11 am on 5/2

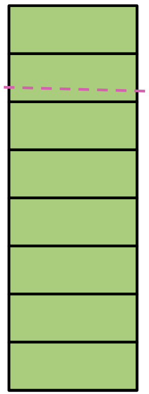
Synchronization Primitives

- Sometimes we want semantics beyond just mutual exclusion
  - Wait for shared resources to become available
  - Allow multiple threads to generate different resources
  - Use certain conditions to decide when to enter a critical section
- Example synchronization problems
  - Producer-Consumer Problem
  - Readers-Writers Problem
- Semaphores
  - Synchronization variable with a non-negative integer value
  - `wait()`: waits for the semaphore to become positive and then decrements by 1
  - `signal()`: increments the semaphore by 1

Producer-Consumer with Locks and Sleep/Wake

Producer

```
while (1) {
  produce an item
  if (count == N)
    sleep();
  acquire(lock);
  insert item in buffer
  count++;
  release(lock);
  if (count == 1)
    wakeup(consumer)
}
```



count = 8

N = 8

Context switch

Consumer

```
while (1) {
  if (count == 0)
    sleep();
  acquire(lock);
  remove item from buffer
  count--;
  release(lock);
  if (count == N-1)
    wakeup(producer)
  consume an item
}
```

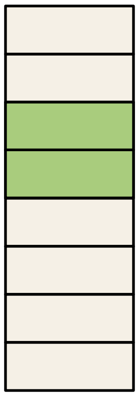
- Naïve attempt to solve the Producer-Consumer problem
- Both threads sleep and never wake up

Producer-Consumer with Semaphores

Producer

```
while (1) {
  produce an item
  wait(empty_count)

  acquire(lock);
  insert item in buffer
  count++;
  release(lock);
  signal(full_count)
}
```



count = 2

N = 8

Consumer

```
while (1) {
  wait(full_count)

  acquire(lock);
  remove item from buffer
  count--;
  release(lock);
  signal(empty_count)

  consume an item
}
```

- This approach works

Semaphore Summary

- Semaphores can be used to solve traditional synchronization problems
  - Enforce critical sections (mutual exclusion)
  - Enable coordination between threads (scheduling)
- But they have some drawbacks:
  - No coordination between the semaphore and the controlled data
  - Used for both critical sections and coordination - this can be confusing!
  - Sometimes hard to use and prone to bugs
- What can we do instead?

Today’s Outline

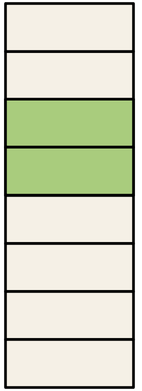
- Condition Variables
  - Another way of synchronizing threads
- Monitors
  - Leverage language support for synchronization
- Deadlock
  - What can go wrong with concurrency?
  - What can we do about it?

Producer-Consumer with Locks and Sleep/Wake

Producer

move acquire earlier

```
while (1) {
  produce an item
  if (count == N)
    sleep();
  acquire(lock);
  insert item in buffer
  count++;
  release(lock);
  if (count == 1)
    wakeup(consumer)
}
```



count = 2

N = 8

Consumer

Context switch

```
while (1) {
  if (count == 0)
    sleep();
  acquire(lock);
  remove item from buffer
  count--;
  release(lock);
  if (count == N-1)
    wakeup(producer)
  consume an item
}
```

move acquire earlier

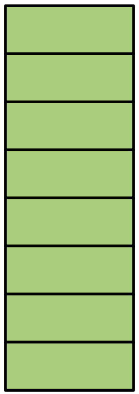
- Naïve attempt - is there another way to fix this?
- The problem was that a context switch could occur between `if` and `sleep`
- What if we moved the calls to `acquire` earlier?

Producer-Consumer with Locks and Sleep/Wake

Producer

replace with atomic `sleep-and-release?`

```
while (1) {
  produce an item
  acquire(lock);
  if (count == N)
    sleep();
  insert item in buffer
  count++;
  release(lock);
  if (count == 1)
    wakeup(consumer)
}
```



count = 2

N = 8

Consumer

```
while (1) {
  acquire(lock);
  if (count == 0)
    sleep();
  remove item from buffer
  count--;
  release(lock);
  if (count == N-1)
    wakeup(producer)
  consume an item
}
```

- Move the calls to acquire earlier
- Does this work?
- No, a thread can sleep while holding the lock!

Condition Variables

- Goal: make it possible to go to sleep inside a critical section, by atomically releasing the lock at the same time we go to sleep
- A synchronization primitive that enables a queue of threads waiting for something inside a critical section
- Condition Variables support three operations:
  - `wait()`: release the lock, go to sleep, wake up and re-acquire the lock when signaled (releasing the lock and going to sleep is atomic)
    - » Also `sleep()` in Nachos
  - `signal()`: wake up a waiting thread, if any
    - » Also `wake()` in Nachos or `notify()`
  - `broadcast()`: wake up all waiting threads, if any
    - » Also `wakeAll()` in Nachos or `notifyAll()`

Condition Variables

- Used in conjunction with locks
  - On creation, must specify which lock it is associated with
  - Must hold the lock when invoking condition variable operations
  - Lock will be atomically released and acquired during `wait()`
- Can be used to implement semaphores (and vice versa)
- Contrast with semaphore:
  - No counting involved
  - Memoryless
    - » If `signal()` is called when no thread is waiting, it does nothing
  - More intuitive to many people
  - More commonly used in modern programming

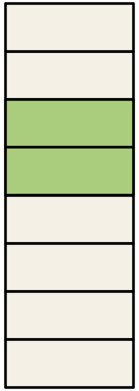
Producer-Consumer with Condition Variables

Producer

critical section

```
while (1) {
  produce an item
  acquire(lock);
  if (count == N)
    wait(not_full);
  insert item in buffer
  count++;
  if (count == 1)
    signal(not_empty);
  release(lock);
}
```

atomically releases the lock



count = 2

N = 8

atomically releases the lock

Consumer

```
while (1) {
  acquire(lock);
  if (count == 0)
    wait(not_empty);
  remove item from buffer
  count--;
  if (count == N-1)
    signal(not_full);
  release(lock);
  consume item
}
```

critical section

- 2 condition variables to indicate when the buffer becomes `not_full` and `not_empty`
- Does this work?

Producer-Consumer with Condition Variables

Producer

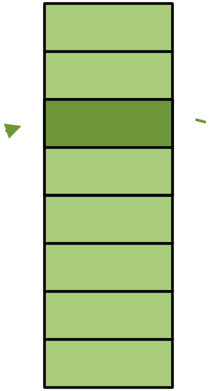
producer 1

producer 2

Producer 1 blocks

Producer 1 produces into a full buffer!

```
while (1) {
  produce an item
  acquire(lock);
  if (count == N)
    wait(not_full);
  insert item in buffer
  count++;
  if (count == 1)
    signal(not_empty);
  release(lock);
}
```



count = 2

N = 8

Consumer

consumer

```
while (1) {
  acquire(lock);
  if (count == 0)
    wait(not_empty);
  remove item from buffer
  count--;
  if (count == N-1)
    signal(not_full);
  release(lock);
  consume item
}
```

- What could go wrong?
  - Producer 1 waits, consumer consumes, but then producer 2 produces!

Signal Semantics – Mesa vs. Hoare

- What happens when `signal()` is called?
  - Only one thread can hold the lock at once
  - Should the signaler or the woken thread run first?
- Mesa semantics
  - Signaler keeps the lock and continues running
  - Waiter is put on the ready queue
  - Used by Nachos, most real operating systems
  - Easier to implement
- Hoare semantics
  - Signaler passes the lock to the waiter, waiter runs immediately

Signal Semantics – Mesa vs. Hoare

- Mesa semantics: the condition is not necessarily true when the signaled thread runs again
  - Returning from `wait()` is only a hint that something has changed
  - Must recheck the conditional case
- Hoare semantics: the condition is true when the signaled thread runs again
  - No need to recheck the conditional case

Mesa semantics

```
while (count == N)
  wait(not_full);
```

Hoare semantics

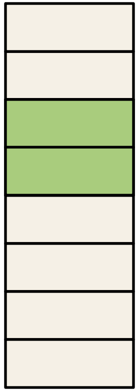
```
if (count == N)
  wait(not_full);
```

Producer-Consumer with Condition Variables

Producer

replace `if` with `while`

```
while (1) {
  produce an item
  acquire(lock);
  while (count == N)
    wait(not_full);
  insert item in buffer
  count++;
  if (count == 1)
    signal(not_empty);
  release(lock);
}
```



count = 2

N = 8

Consumer

```
while (1) {
  acquire(lock);
  while (count == 0)
    wait(not_empty);
  remove item from buffer
  count--;
  if (count == N-1)
    signal(not_full);
  release(lock);
  consume item
}
```

replace `if` with `while`

- Recheck the condition by replacing the `if` with a `while`
- Does this work?
- Yes!

Common Pitfalls with Condition Variables #1

- CVs cannot be "tested"
- Need to maintain a separate flag

```
acquire(lock);
...
while (cond_var != true)
    wait(cond_var);
...
release(lock);
```

```
acquire(lock);
...
while (flag != true)
    wait(cond_var);
...
release(lock);
```

Common Pitfalls with Condition Variables #2

- Do not release the lock before using the CV
  - Using a CV requires that the thread holds the lock
- Purpose of a CV is to enable threads to block while in a critical section

```
acquire(lock);
...
release(lock);
wait(cond_var);
acquire(lock);
...
release(lock);
```

```
acquire(lock);
...

wait(cond_var);

...
release(lock);
```

Common Pitfalls with Condition Variables #3

- Need to hold the lock while testing the condition
- The condition involves shared variables (e.g., `flag`) and is at risk of race conditions otherwise

```
...
while (flag != true) {
  acquire(lock);
  wait(cond_var);
  release(lock);
}
...
```

```
acquire(lock);
...
while (flag != true) {
  wait(cond_var);
}
...
release(lock);
```

Today's Outline

- Condition Variables
  - Another way of synchronizing threads
- Monitors
  - Leverage language support for synchronization
- Deadlock
  - What can go wrong with concurrency?
  - What can we do about it?

Monitors

- A monitor is a programming language construct that controls access to shared data
  - Synchronization code is added by the compiler, enforced at runtime
- A monitor is a module that encapsulates:
  - Shared data structures
  - Procedures that operate on the shared data structures
  - Synchronization between concurrent threads that invoke the procedures
- A monitor protects its data from unstructured access
- It guarantees that threads accessing its data through its procedures interact only in legitimate ways

Monitor Semantics

- A monitor guarantees mutual exclusion
  - Only one thread can execute any monitor procedure at any time (the thread is “in the monitor”)
- Threads can use condition variables within a monitor
  - If a thread blocks within a monitor, another one can enter

Producer-Consumer with a Monitor

- Locking is implicit
  - Compiler adds the code
  - Equivalent to each procedure in the monitor calling `acquire()` on entry and `release()` on exit

```
Monitor producer_consumer {
  Condition not_full;
  Condition not_empty;

  void put_resource() {
    ...
    wait(not_full);
    ...
    signal(not_empty);
}

  void get_resource() {
    ...
    wait(not_empty);
    ...
    signal(not_full);
  }
}
```

Synchronization Primitives Summary

- Locks
  - Only provide mutual exclusion
- Semaphores
  - Provide mutual exclusion (binary semaphores)
  - Enable coordination between threads (counting semaphores)
- Condition variables
  - Synchronization point to wait for events
  - Used with locks or inside monitors
- Monitors
  - Synchronized execution using high-level language support

Synchronization in Real Life

Consider locks, semaphores, and condition variables (not monitors)

- Example scenarios:
  - Crowded lab space counting semaphore
    - Goal: only 8 people or fewer can be in the lab at once
  - Too much talking lock or binary semaphore
    - Goal: avoid multiple people talking at the same time
  - Feed the picky eaters condition variable + lock
    - Each kid wants to eat specific foods for dinner (e.g., kid 1: 1 cookie + 2 sandwiches, kid 2: 5 cookies + 1 carrot)
    - Cooks prepare food (e.g., 12 cookies, 30 carrots)
    - Goal: a kid can only take food when they can take their whole dinner at once
- Which synchronization primitive(s) would you use? Why?
- What does each primitive represent?

Today's Outline

- Condition Variables
  - Another way of synchronizing threads
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Deadlock

- Incorrect use of synchronization can block all threads
  - We have seen examples already!
- Threads acquiring resources generate dependencies
  - Locks, semaphores, etc. protect resources
- Example:
  - T1 tries to acquire a resource that T2 holds and vice-versa
  - They can never make progress
- This is a deadlock

Dining Philosophers' Problem

- Dijkstra 1971
- Philosophers eat and think
- Eating requires two forks
    - Pick up one fork at a time
- Same number of forks as philosophers
- What can go wrong?
- What if they all pick up their right fork at the same time?

Deadlock Definition

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

Thread 1

```
acquire(lock1);
...
acquire(lock2);
```

Deadlock!

Thread 2

```
acquire(lock2);
...
acquire(lock1);
```

Deadlock with Join

- How can we cause a deadlock with `join()`?

Thread A

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

Thread B

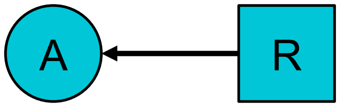
```
...
A.join();
...
```

Conditions for Deadlock

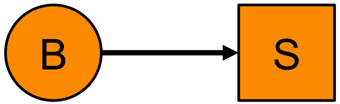
- Deadlock can exist if an only if the following conditions hold simultaneously:
  - Mutual exclusion: a resource is assigned to at most one thread at once
  - Hold and wait: threads holding resources can request new resources while continuing to hold old resources
  - No preemption: resources cannot be taken away once obtained
  - Circular wait: one thread waits for another in a circular fashion
- Eliminating any condition eliminates deadlock!

Resource Allocation Graph

- We can illustrate deadlock using a resource allocation graph (RAG)
- Thread A holds resource R

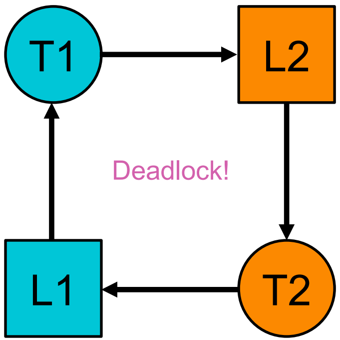


- Thread B requests resource S



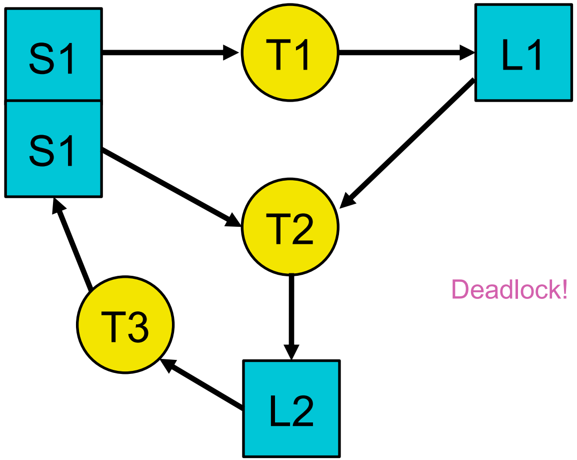
- If the graph has a cycle: deadlock may exist
- No cycles: no deadlock

- Example:
  - Thread 1 holds lock 1
  - Thread 2 holds lock 2
  - Each requests the others' lock

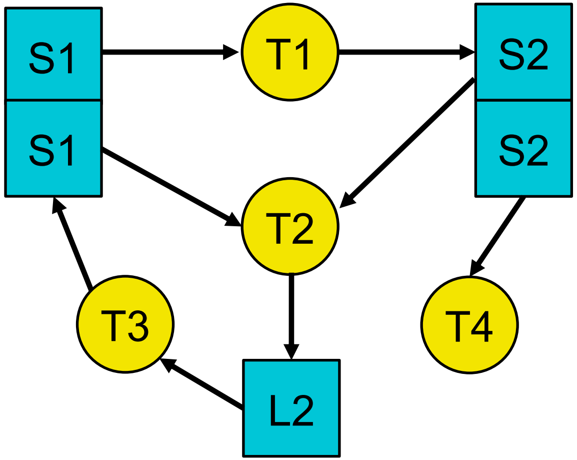


Resource Allocation Graph Examples

- Represent multiple resources with multiple boxes (e.g., with semaphores)
- Is there a deadlock?



Deadlock!



A cycle but no deadlock

Multi-Unit vs. Single-Unit Resources

- Multiple resources of some types
  - If the graph has a cycle: deadlock may exist
- Single resource of each type
  - If the graph has a cycle: deadlock exists
  - Useful for tracking locks

Strategies for Dealing with Deadlock

- Ignore the problem
  - Ostrich algorithm
- Prevention
  - Make it impossible for deadlock to happen
- Avoidance
  - Control allocation of resources
- Detection and Recovery
  - Look for a cycle in dependencies
- To be continued next class…

For next class…

- Read chapters 7 and 8