Deadlock and Advanced Synchronization

CS439: Principles of Computer Systems

February 16, 2015

Last Time

- Software abstractions for Mutual Exclusion
  - Monitors
    - Condition Variables (Zero or more)
    - Locks (Exactly One!)
- Readers and Writers

Today's Agenda

- How to Program Multi-threaded code
- Dining Philosophers
- Deadlocks
  - What causes them
- Advanced Synchronization
- Pemberley!

Writing Multi-threaded (User-Level) Code

Designing Multithreaded Programs

- Building a shared object class (or pseudo-class) involves familiar steps:
  - Decompose the problem into objects
  - For each object:
    - define a clear interface
    - implement methods that manipulate the state appropriately
- The new steps are straightforward:
  - Add a lock
  - Add code to acquire and release the lock
  - Identify synchronization points and add condition variables
  - Add loops to check resource status and wait using condition variables
  - Add signal() and broadcast() calls

Managing Locks

- Add a lock as a member variable for each object in the class to enforce mutual exclusion on the object's shared state
- Acquire a lock at the start of each public method
- Release the lock at the end of each public method
  - You will be tempted to acquire/release a lock midway through a method.
  - RESIST!

Identifying Condition Variables

- Ask yourself: when can this function wait?
- Map each opportunity for waiting to a condition variable
  - full and empty in producers/consumers
- You may be able to manage with less condition variables
  - such as somethingChanged
  - but you must call broadcast() and not signal() (why?)

Waiting Using Condition Variables

- Every call to Condition::Wait() should be enclosed in a loop
- Loop tests the appropriate resource
- When Condition::Wait() is called, **all invariants must hold**
  - Remember, you are releasing the lock!

Signal vs. Broadcast

- It is always safe to use `broadcast()` instead of `signal()`
  - Because you are *also* waiting in a `while`
  - Only performance is affected
- `signal()` is preferable when
  - At most one waiting thread can make progress
  - Any thread waiting on the condition variable can make progress
- `broadcast()` is preferable when
  - Multiple waiting threads may be able to make progress
  - The same condition variable is used for multiple predicates
    - some waiting threads can make progress, others can't

The Six Commandments

- **Thou shalt always do things the same way**
  - Habit allows you to focus on the core problem
  - Easier to review, maintain, and debug your code
- **Thou shalt always synchronize with locks and condition variables**
  - Condition variables and locks make code clearer

The Six Commandments

- **Thou shalt always acquire the lock at the beginning of a function and release it at the end**
  - Put a chunk of code that requires a lock into its own function
- **Thou shalt always hold lock when operating on a condition variable**
  - Condition variables are useless without shared state
  - Shared state should only be accessed using a lock

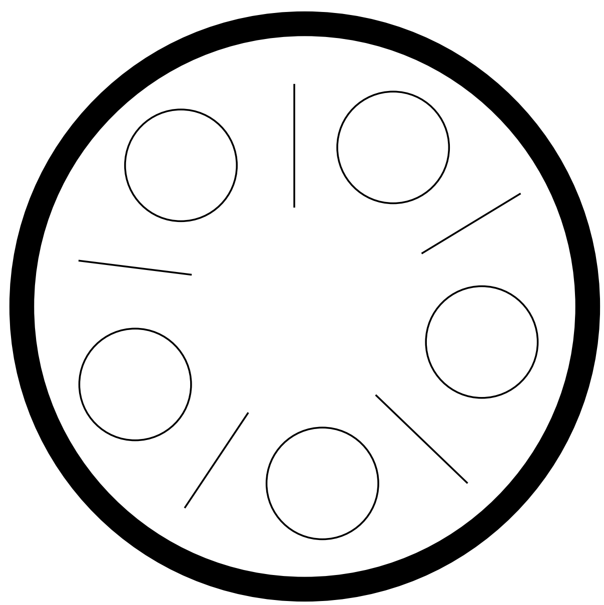
The Six Commandments

- **Thou shalt always wait in a while loop**
  - `while()` works every time `if()` does
  - Makes signals hints
  - Protects against spurious wake ups
- **(Almost) Never sleep()**
  - Use `sleep()` only if an action should occur at a specific real time
  - Never use `sleep()` to wait for an event

Dining Philosophers

Dining Philosophers

N philosophers are sitting at a table with N chopsticks, each needs two chopsticks to eat, and each philosopher alternates between thinking, getting hungry, and eating.



Dining Philosophers: Solution

```
do forever:
    think
    get hungry
    wait(chopstick[i])
    wait(chopstick[(i+1) % N])

    eat

    signal(chopstick[i])
    signal(chopstick[(i+1) % N])
```

Does this solution work?

A. Yes
B. No

Deadlock

What is Deadlock?

- *Deadlock* occurs when two or more threads are waiting for an event that can only be generated by these same threads
- Deadlock is not starvation
  - Starvation can occur without deadlock
    - occurs when a thread waits indefinitely for some resources, but other threads are actually using it
  - But deadlock does imply starvation
- We will be discussing how deadlock can occur in the multi-threaded (or multiprocess) code we write (there are other places deadlock may occur)

Deadlock Example

```
Producer{
    lock->down()
    empty->down()

    <do stuff>

   full->up()
   lock->up()
}
```

```
Consumer{
    full->down()
    lock->down()

    <do stuff>

    empty->up()
    lock->up()
}
```

Conditions for Deadlock

Deadlock can happen **if all** of the following conditions hold:

1. **Mutual Exclusion**: at least one thread must hold a resource in non-sharable mode
2. **Hold and Wait**: at least one thread holds a resources and is waiting for other resources to become available. A different thread holds the resource.
3. **No Pre-emption**: a thread only releases a resource voluntarily; another thread or the OS cannot force the thread to release the resource
4. **Circular Wait**: A set of waiting threads $\{t_1, \ldots, t_n\}$ where t_i is waiting on t_{i+1} ($i=1$ *to* n) and t_n is waiting on t_1

Deadlock Prevention

Prevent deadlock by insuring that at least one of the necessary conditions doesn't hold

1. **Mutual Exclusion**: make resources sharable
2. **Hold and Wait**: guarantee a thread cannot hold one resource when it requests another (or must request all at once)
3. **No Pre-emption**: If a thread requests a resource that cannot be immediately allocated to it, then the OS pre-empts all the resources the thread is currently holding. Only when all the resources are available will the OS restart the thread
4. **Circular Wait**: Impose an ordering on the resources and request them in order

Deadlock Prevention: Resource Ordering

- Order all locks (or semaphores or resources)
- All code grabs locks in a predefined order
- Complications:
  – Maintaining global order is difficult in a large project
  – Global order can force a client to grab a lock earlier than it would like, tying up a resource for longer than necessary

Dining Philosophers: Possible Solutions

- *Prevent circular wait by having sufficient resources*: Kick out a philosopher
- *Prevent circular wait by ordering resources*:
  - Odd philosophers pick up right then left
  - Even philosophers pick up left then right
- *Prevent hold-and-wait*: Only let a philosopher pick up chopsticks if both are available
- *Pre-empt resources*: Designate a philosopher as the head philosopher. Allow that philosopher to take a chopstick from a neighbor if that neighbor is not currently eating.
- *Don't require mutual exclusion*: ?

Advanced Synchronization

A House of Cards?

- Locks and condition variables are a great way to regulate access to a *single* shared object…
- … but general multi-threaded programs touch *multiple* shared objects
- How can we atomically modify multiple shared objects to maintain
  - Safety: prevent applications from seeing inconsistent states
  - Liveness: avoid deadlock

?

Multi-Object Synchronization

- Transfer $100 from account A to account B

  A->subtract(100)

  B->add(100)

  Individual operations are atomic.
  Sequence is not.

- How should we ensure atomicity?
  - One lock for each account?
  - One lock for all accounts?
  - All accounts at one bank?
  - All accounts everywhere?

One Big Lock

- Simple
  - Relatively easy to get correct
- Often not great for performance
  - No advantage from multi-threading for that part of your code
  - No advantage of multicore in that part of your code

Fine-Grained Locking

- Better for performance
  - This will matter more in the kernel than in an application (the kernel effects every application!)
- Complex
  - May need to acquire multiple locks to accomplish a task (a lock for each account?)
  - Incorrect code becomes more likely
  - Deadlock

Two-Phase Locking

- Two-phase locking requires that the thread:
  1. Acquire all locks it will need

     If all locks cannot be acquired, release any already acquired and begin again
  2. Make necessary changes, commit, and release locks
- All unlocks happen at the commit

- Thus, B cannot see any of A’s changes until A commits and releases the lock
  - Provides serializability
  - May cause deadlock

Transactions

- *Transactions* group actions together so that they are:
  - *atomic*: they all happen or they all don't
  - *serializable*: transactions appear to happen one after the other
  - *durable*: once it happens, it sticks
- Critical sections give us atomicity and serializability, but not durability

Achieving Durability

To get durability, we need to be able to:

- *Commit*: indicate when a transaction is finished
- *Roll back*: recover from an *aborted* transaction
  - If we have a failure in the middle of a transaction, we need to be able to undo what we have done so far
- In other words, we do a set of operations tentatively.
  - If we get to the commit stage, we are okay.
  - If not, roll back operations as if the transaction never happened.

Implementing Transactions

- Key idea: Turn multiple disk updates into a single disk write!

```
begin transaction
    x = 300
    y = 512
Commit
```

- Keep *write-ahead* (or *redo*) log on disk of all changes in the transaction
- The log records everything the OS does (or tries!) to do
- Once the OS writes both changes on the log, the transaction is committed
- Then *write-behind* changes to the disk, logging all writes
- If the crash comes after a commit, the log is replayed

iClicker Question

Imagine two threads executing this code:

```
begin transaction
 lock x, y
   x = x + 3
   y = y + 5
 unlock x, y
Commit
```

Does this code work?

A. Yes
B. No

Implementing Multi-Threaded Transactions

```
begin transaction
 lock x, y
    x = x + 3
    y = y + 5
 unlock x, y
Commit
```

Given two threads A & B that execute that code in the following sequence:

1. A gets the lock, reads an modifies x and y, writes to the log, and unlocks
2. The B grabs the lock before A commits
3. B reads A's modifications, then modifies x and y, writes to the log, unlocks, and commits
4. Then the system crashes before A commits

In the transaction log…

Assuming all goes well and initial values of x and y are 0:

```
Begin transaction
x=3
y=5
Commit
Begin transaction
x=6
y=10
Commit
```

Pemberley!

Summary

- Code concurrent programs very carefully to help prevent deadlock over resources managed by the program
- Deadlock is a situation in which a set of threads/ processes cannot proceed because each requires resources held by another member of the set
- Sometimes more fine-grained synchronization techniques are required for efficiency, but you must be extra careful
- Sometimes serializability is necessary; in those cases, use two-phase locking
- Sometimes durability is necessary; in those cases, use transactions

Announcements

- Homework 4 due Friday
- Project 1 is posted is due 2/27
- Exam 1 is NEXT week! (Wednesday, 2/25! 7p!)
  - If you have a conflict, you should have already notified me via email.