CSE 332: Locks and Deadlocks

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Announcements
Recall Bank Account Problem

class BankAccount {
    private int balance = 0;
    synchronized int getBalance() {
        return balance;
    }
    synchronized void setBalance(int x) {
        balance = x;
    }
    synchronized void withdraw(int amount) {
        int b = getBalance();
        if (amount > b) {
            throw ...
        }
        setBalance(b - amount);
    }
    // deposit would also use synchronized
}

Call to setBalance in withdraw
    - tries to lock this
Re-Entrant Lock

• A re-entrant lock (a.k.a. recursive lock)
  - If a thread holds a lock, subsequent attempts to acquire the same lock in the same thread won’t block
  - withdraw can acquire the lock and setBalance can also acquire it
  - implemented by maintaining a count of how many times each lock is acquired in each thread, and decrementing the count on each release.

• Java synchronize locks are re-entrant
Lock everything? No.

For every memory location (e.g., object field), obey at least one of the following:

1. **Thread-local**: only one thread sees it
2. **Immutable**: read-only
3. **Shared-and-mutable**: control access via a lock
Thread local

Whenever possible, do not share resources
  – easier to give each thread its own local copy
  – only works if threads don’t need to communicate via resource

In typical concurrent programs, the vast majority of objects should be thread local: shared memory should be rare—minimize it
Immutable

If location is read-only, no synchronization is necessary

Whenever possible, do not update objects
  – make new objects instead!
  – one of the key tenets of *functional programming* (CSE 341)

In practice, programmers usually over-use mutation – minimize it
The rest: keep it synchronized
Other Forms of Locking in Java

- Java provides many other features and details. See, for example:
  - Chapter 14 of CoreJava, Volume 1 by Horstmann/Cornell
  - Java Concurrency in Practice by Goetz et al
Locking Guidelines

• Correctness
• Consistency: make it well-defined
• Granularity: coarse to fine
• Critical Sections: make them small, atomic
• Leverage libraries
Consistent Locking

- Clear mapping of locks to resources
  - followed by all methods
  - clearly documented
  - same lock can guard multiple resources

- what’s a resource? Conceptual:
  - object
  - field
  - data structure (e.g., linked list, hash table)
Lock Granularity

- **Coarse grained:** fewer locks, more objects per lock
  - e.g., one lock for entire data structure (e.g., linked list)
  - advantage:
  - disadvantage:

- **Fine grained:** more locks, fewer objects per lock
  - e.g., one lock for each item in the linked list
Lock Granularity

Example: hashtable with separate chaining
  - coarse grained: one lock for whole table
  - fine grained: one lock for each bucket

Which supports more concurrency for \texttt{insert} and \texttt{lookup}?

Which makes implementing \texttt{resize} easier?

Suppose hashtable maintains a \texttt{numElements} field. Which locking approach is better?
Critical Sections

• Critical sections:
  - how much code executes while you hold the lock?
  - want critical sections to be short
  - make them “atomic”: think about smallest sequence of operations that have to occur at once (without data races, interleavings)
Critical Sections

• Suppose we want to change a value in a hash table
  - assume one lock for the entire table
  - computing the new value takes a long time ("expensive")

```java
synchronized (lock) {
    v1 = table.lookup(k);
    v2 = expensive(v1);
    table.remove(k);
    table.insert(k, v2);
}
```
Critical Sections

• Suppose we want to change a value in the hash table
  - assume one lock for the entire table
  - computing the new value takes a long time ("expensive")
  - will this work?

```java
synchronized(lock) {
    v1 = table.lookup(k);
}

v2 = expensive(v1);

synchronized(lock) {
    table.remove(k);
    table.insert(k,v2);
}
```
Critical Sections

- Suppose we want to change a value in the hash table
  - assume one lock for the entire table
  - computing the new value takes a long time ("expensive")
  - convoluted fix:

```java
done = false;
while(!done) {
    synchronized(lock) {
        v1 = table.lookup(k);
    }
    v2 = expensive(v1);
    synchronized(lock) {
        if(table.lookup(k)==v1) {
            done = true; // I can exit the loop!
            table.remove(k);
            table.insert(k,v2);
        }
    }
}
```
Leverage Libraries

• Use built-in libraries whenever possible
• In “real life”, it is unusual to have to write your own data structure from scratch
  – Implementations provided in standard libraries
  – Point of CSE332 is to understand the key trade-offs, abstractions, and analysis of such implementations

• Especially true for concurrent data structures
  – Very difficult to provide fine-grained synchronization without race conditions
  – Standard thread-safe libraries like ConcurrentHashMap written by world experts
Another Bank Operation

Consider transferring money:

```java
class BankAccount {
    ...
    synchronized void withdraw(int amt) {...}
    synchronized void deposit(int amt) {...}
    synchronized void transferTo(int amt,
                                  BankAccount a) {
        this.withdraw(amt);
        a.deposit(amt);
    }
}
```

What can go wrong?
Deadlock

**x** and **y** are two different accounts

Time

- **Thread 1:** `x.transferTo(1,y)`
- **Thread 2:** `y.transferTo(1,x)`

---

acquire lock for **x**
withdraw from **x**

block on lock for **y**

acquire lock for **y**
withdraw from **y**

block on lock for **x**
Dining Philosopher’s Problem

• 5 Philosopher’s eating rice around a table
• one chopstick to the left and right of each
• first grab the one on your left, then on your right…
Deadlock = Cycles

- Multiple threads depending on each other in a cycle
  - T2 has lock that T1 needs
  - T3 has lock that T2 needs
  - T1 has lock that T3 needs

- Solution?
How to Fix Deadlock?

In Banking example

class BankAccount {
    ...
    synchronized void withdraw(int amt) { ... }  
    synchronized void deposit(int amt) { ... }  
    synchronized void transferTo(int amt, BankAccount a) {
        this.withdraw(amt);
        a.deposit(amt);
    }  
}
How to Fix Deadlock?

Separate withdraw from deposit

```java
class BankAccount {
    ...
    synchronized void withdraw(int amt) {...}
    synchronized void deposit(int amt) {...}
    synchronized void transferTo(int amt, BankAccount a) {
        this.withdraw(amt);
        a.deposit(amt);
    }
}
```

Problems?
Possible Solutions

1. `transferTo` not synchronized
   - exposes intermediate state after `withdraw` before `deposit`
   - may be okay here, but exposes wrong total amount in bank

2. Coarsen lock granularity: one lock for each pair of accounts allowing transfers between them
   - works, but sacrifices concurrent deposits/withdrawals

3. Give every bank-account a unique ID and always acquire locks in the same ID order
   - *Entire program* should obey this order to avoid cycles
Ordering Accounts

Transfer from bank account 5 to account 9

1. lock A5
2. lock A9
3. withdraw from A5
4. deposit to A9
Ordering Accounts

Transfer from bank account 5 to account 9

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Transfer from bank account 9 to account 5

1. lock
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Ordering Accounts

Transfer from bank account 5 to account 9

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Transfer from bank account 9 to account 5

1. lock
2. lock
3. withdraw from
4. deposit to

No interleavings will produce deadlock!
- T1 cannot block on A9 until it has A5
- T2 cannot acquire A9 until it has A5
Banking Without Deadlocks

class BankAccount {
    ...
    private int acctNumber; // must be unique
    void transferTo(int amt, BankAccount a) {
        if (this.acctNumber < a.acctNumber)
            synchronized(this) {
                synchronized(a) {
                    this.withdraw(amt);
                    a.deposit(amt);
                }
            }
        else
            synchronized(a) {
                synchronized(this) {
                    this.withdraw(amt);
                    a.deposit(amt);
                }
            }
    }
}
Lock Ordering

• Useful in many situations
  – e.g., when moving an item from work queue A to B, need to acquire locks in a particular order

• Doesn’t always work
  – not all objects can be naturally ordered
  – Java StringBuffer append is subject to deadlocks
    ‣ thread 1: append string A onto string B
    ‣ thread 2: append string B onto string A
Locking a Hashtable

• Consider a hashtable with
  – many simultaneous \texttt{lookup} operations
  – rare \texttt{insert} operations

• What’s the right locking strategy?
Read vs. Write Locks

• Recall race conditions
  – two simultaneous write to same location
  – one write, one simultaneous read

• But two simultaneous reads OK

• Synchronize is too strict
  – blocks simultaneous reads
Readers/Writer Locks

A new synchronization ADT: The readers/writer lock

• A lock’s states fall into three categories:
  – “not held”
  – “held for writing” by one thread
  – “held for reading” by one or more threads

  \[0 \leq \text{writers} \leq 1\]
  \[0 \leq \text{readers} \leq \text{writers} \times \text{readers} = 0\]

• **new**: make a new lock, initially “not held”
• **acquire_write**: block if currently “held for reading” or “held for writing”, else make “held for writing”
• **release_write**: make “not held”
• **acquire_read**: block if currently “held for writing”, else make/keep “held for reading” and increment **readers count**
• **release_read**: decrement readers count, if 0, make “not held”
In Java

Java’s *synchronized* statement does not support readers/writer
Instead, library
java.util.concurrent.locks.ReentrantReadWriteLock

• Different interface: methods *readLock* and *writeLock* return objects that themselves have *lock* and *unlock* methods
Concurrency Summary

• Parallelism is powerful, but introduces new concurrency issues:
  – Data races
  – Interleaving
  – Deadlocks

• Requires synchronization
  – Locks for mutual exclusion

• Guidelines for correct use help avoid common pitfalls