CSE 332: Concurrency and Locks

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Banking

Two threads both trying to **withdraw(100)** from the **same account**:

• Assume initial **balance** 150

```java
class BankAccount {
    private int balance = 0;
    int getBalance() { return balance; }
    void setBalance(int x) { balance = x; }
    void withdraw(int amount) {
        int b = getBalance();
        if (amount > b)
            throw new WithdrawTooLargeException();
        setBalance(b - amount);
    }
    ...
    // other operations like deposit, etc.
}
```

**Thread 1**

```java```
x.withdraw(100);
```

**Thread 2**

```java```
x.withdraw(100);
```
A bad interleaving

Interleaved **withdraw(100)** calls on the same account
– Assume initial **balance == 150**

```
Thread 1

int b = getBalance();
if(amount > b)
    throw new ...
setBalance(b - amount);
```

```
Thread 2

int b = getBalance();
if(amount > b)
    throw new ...
setBalance(b - amount);
```
How to fix?

No way to fix by rewriting the program
– can always find a bad interleaving -> violation
– need some kind of synchronization

```
int b = getBalance();
if (amount > b)
    throw new ...
setBalance(b - amount);
```

```
int b = getBalance();
if (amount > b)
    throw new ...
setBalance(b - amount);
```
Race Conditions

A race condition: program executes incorrectly due to unexpected order of threads

Two kinds

1. data race:
   - two threads write a variable at the same time
   - one thread writes, another reads simultaneously

2. bad interleaving: wrong result due to unexpected interleaving of statements in two or more threads
Concurrency

Concurrency:
Correctly and efficiently managing access to shared resources from multiple possibly-simultaneous clients

Requires coordination
- synchronization to avoid incorrect simultaneous access:
  - make others block (wait) until the resource is free

Concurrent applications are often non-deterministic
- how threads are scheduled affects what operations happen first
- non-repeatability complicates testing and debugging
- must work for all possible interleavings!!
Concurrency Examples

- Bank Accounts
- Airline/hotel reservations
- Wikipedia
- Facebook
- Databases
Locks

• Allow access by at most one thread at a time
  – “mutual exclusion”
  – make others block (wait) until the resource is free
  – called a mutual-exclusion lock or just lock, for short

• Critical sections
  – code that requires mutual exclusion
  – defined by the programmer (compiler can’t figure this out)
We define **Lock** as an ADT with operations:

- **new**: make a new lock, initially “not held”
- **acquire**: blocks if this lock is already currently “held”
  - Once “not held”, makes lock “held” (one thread gets it)
- **release**: makes this lock “not held”
  - If >= 1 threads are blocked on it, exactly 1 will acquire it

Allow access to at most one thread at a time

How can this be implemented?

- acquire (check “not held” -> make “held”) **cannot be interrupted**
- special hardware and operating system-level support
Basic idea  (note Lock is not an actual Java class)

class BankAccount {
    private int balance = 0;
    private Lock lk = new Lock();
    ...
    void withdraw(int amount) {
        lk.acquire(); // may block
        int b = getBalance();
        if (amount > b)
            throw new WithdrawTooLargeException();
        setBalance(b - amount);
        lk.release();
    }
    // deposit would also acquire/release lk
}
Common Mistakes

• Forgetting to release locks
  – e.g., because of Throws (previous slide)

• Too few locks
  – e.g., all bank accounts share a single lock

• Too many locks
  – separate locks for deposit, withdraw
What Do We Lock?

• Class
  – e.g., all bank accounts?

• Object
  – e.g., a particular account?

• Field
  – e.g., balance

• Code fragment
  – e.g., withdraw
Synchronized: Locks in Java

Java has built-in support for locks

```java
synchronized (expression) {
  statements
}
```

1. *expression* evaluates to an **object**
   - Any **object** (but not primitive types) can be a lock in Java

2. Acquires the lock, blocking if necessary
   - If you get past the `{`, you have the lock

3. Releases the lock at the matching `}`
   - even if control leaves due to `throw`, `return`, etc.
   - so **impossible** to forget to release the lock
class BankAccount {
    private int balance = 0;
    private Object lk = new Object();
    int getBalance() {
        synchronized (lk) {
            return balance;
        }
    }
    void setBalance(int x) {
        synchronized (lk) {
            balance = x;
        }
    }
    void withdraw(int amount) {
        synchronized (lk) {
            int b = getBalance();
            if (amount > b)
                throw ...
            setBalance(b - amount);
        }
    }
    // deposit would also use synchronized(lk)
}
Shorthand

Usually simplest to use the class object itself as the lock

```java
synchronized (this) {
    statements
}
```

This is so common that Java provides a shorthand:

```java
synchronized {
    statements
}
```
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
    }
}

Final Version
Stack Example

class Stack<E> {
    private E[] array = (E[]) new Object[SIZE];
    int index = -1;
    boolean isEmpty() {
        return index == -1;
    }
    void push(E val) {
        array[++index] = val;
    }
    E pop() {
        if(isEmpty())
            throw new StackEmptyException();
        return array[index--];
    }
}
Why Wrong?

• IsEmpty and push are one-liners. What can go wrong?
  – ans: one line, but multiple operations
  – `array[++index] = val` probably takes at least two ops
  – data race if two pushes happen simultaneously
class Stack<E> {
    private E[] array = (E[]) new Object[SIZE];
    int index = -1;
    synchronize boolean isEmpty() {
        return index == -1;
    }
    synchronize void push(E val) {
        array[++index] = val;
    }
    synchronize E pop() {
        if(isEmpty())
            throw new StackEmptyException();
        return array[index--];
    }
}
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

![Diagram showing memory regions and their relationships.](image-url)
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