CSE 332: Data Structures & Parallelism

Lecture 17: Shared-Memory Concurrency & Mutual Exclusion

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Autumn 2016
Toward sharing resources (memory)

So far, we have been studying parallel algorithms using the fork-join model

- Reduce span via parallel tasks

Fork-Join algorithms all had a very simple structure to avoid race conditions

- Each thread had memory “only it accessed”
  - Example: each array sub-range accessed by only one thread
- Result of forked process not accessed until after join() called
- So the structure (mostly) ensured that bad simultaneous access wouldn’t occur

Strategy won’t work well when:

- Memory accessed by threads is overlapping or unpredictable
- Threads are doing independent tasks needing access to same resources (rather than implementing the same algorithm)
Each thread accesses a different sub-range of the array: Array is shared, but no overlap

```java
class SumTask extends RecursiveTask<Integer> {
    int lo; int hi; int[] arr; // fields to know what to do
    SumTask(int[] a, int l, int h) { ... }
    protected Integer compute(){// return answer
        if(hi - lo < SEQUENTIAL_CUTOFF) {
            int ans = 0; // local var, not a field
            for(int i=lo; i < hi; i++)
                ans += arr[i];
            return ans;
        } else {
            SumTask left = new SumTask(arr,lo,(hi+lo)/2);
            SumTask right= new SumTask(arr,(hi+lo)/2,hi);
            left.fork(); // fork a thread and calls compute
            int rightAns = right.compute(); // call compute directly
            int leftAns = left.join(); // get result from left
            return leftAns + rightAns;
        }
    }
}
static final ForkJoinPool POOL = new ForkJoinPool();
int sum(int[] arr){
    SumTask task = new SumTask(arr,0,arr.length)
    return POOL.invoke(task);
}
```
Really sharing memory between Threads

2 Threads, each with own unshared call stack and “program counter”

Heap for all objects and static fields, shared by all threads
Sharing a Queue....

- Imagine 2 threads, running at the same time,
- both with access to a shared linked-list based queue (initially empty)

```java
enqueue(x) {
    if (back == null) {
        back = new Node(x);
        front = back;
    } else {
        back.next = new Node(x);
        back = back.next;
    }
}
```
Sharing a Queue....

- Imagine 2 threads, running at the same time, both with access to a shared linked-list based queue (initially empty)

```java
enqueue(x) {
    if(back==null){
        back=new Node(x);
        front=back;
    } else{
        back.next = new Node(x);
        back = back.next;
    }
}
```

- Each thread has own program counter (and local stack)
- Queue is shared, so both threads indirectly use the same ‘front’ and ‘back’ (which is the whole point of sharing the queue)
- We have no guarantee what happens first between different threads; they can (and will) arbitrarily ‘interrupt’ each other
- Many things can go wrong: say, one tries to enqueue “a”, the other “b”, and both verify that back is ‘null’ before other sets back
  - Result: One assignment of back will be ‘forgotten’
- In general, any ‘interleaving’ of results is possible if enqueue were called at the same time for both
Concurrent Programming

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

Requires coordination, particularly synchronization to avoid incorrect simultaneous access: make somebody block (wait) until the resource is free
  - join is not what we want
  - Want to block until another thread is “done using what we need” not “completely done executing”

Even correct concurrent applications are usually highly non-deterministic
  - how threads are scheduled affects what operations happen first
  - non-repeatability complicates testing and debugging
Concurrency Examples

What if we have multiple threads:

1. Processing different bank-account operations
   - What if 2 threads change the same account at the same time?

2. Using a shared cache (e.g., hashtable) of recent files
   - What if 2 threads insert the same file at the same time?

3. Creating a pipeline (think assembly line) with a queue for handing work from one thread to next thread in sequence?
   - What if enqueuer and dequeuer adjust a circular array queue at the same time?
Why threads?

Unlike parallelism, not about implementing algorithms faster

But threads still useful for:

- *Code structure for responsiveness*
  - Example: Respond to GUI events in one thread while another thread is performing an expensive computation

- *Processor utilization (mask I/O latency)*
  - If 1 thread “goes to disk,” have something else to do

- *Failure isolation*
  - Convenient structure if want to *interleave* multiple tasks and do not want an exception in one to stop the other
Sharing, again

It is common in concurrent programs that:

- Different threads might access the same resources in an unpredictable order or even at about the same time

- Program correctness requires that simultaneous access be prevented using synchronization

- **Simultaneous access is rare**
  - Makes testing difficult
  - Must be much more disciplined when designing / implementing a concurrent program
  - Will discuss common idioms known to work
Canonical example

Correct code in a single-threaded world

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.
}
Interleaving

Suppose:
- Thread T1 calls x.withdraw(100)
- Thread T2 calls y.withdraw(100)

If second call starts before first finishes, we say the calls **interleave**
- Could happen even with one processor since a thread can be **pre-empted** at any point for time-slicing
  - e.g. T1 runs for 50 ms, pauses somewhere, T2 picks up for 50ms

If x and y refer to different accounts, no problem
- “You cook in your kitchen while I cook in mine”
- But if x and y alias, possible trouble...
Activity: What is the balance at the end?

Two threads both trying to `withdraw()` 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);
```

1/14/2016

Thread 2

```java
x.withdraw(75);
```
Activity: A **bad interleaving**

Interleaved `withdraw()` calls on the same account

- Assume initial `balance == 150`
- This *should* cause a `WithdrawTooLarge` exception

Thread 1: `withdraw(100)`

```java
int b = getBalance();
```

```java
b = 150
```

Thread 2: `withdraw(75)`

```java
int b = getBalance();
if (amount > b)
    throw new ...;
setBalance(b - amount);
```
Activity: A “good” execution is also possible

Interleaved `withdraw()` calls on the same account

- Assume initial `balance == 150`
- This *should* cause a `WithdrawTooLarge` exception

Thread 1: `withdraw(100)`

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

Thread 2: `withdraw(75)`

```java
int b = getBalance();
if(amount > b)
    throw new ...;
setBalance(b - amount);
```
Example: A bad interleaving

Interleaved `withdraw(100)` calls on the same account

- Assume initial `balance == 150`
- This *should* cause a `WithdrawTooLarge` exception

```
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);
```
A bad fix, Another bad interleaving

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

- Assume initial balance 150
- This should cause a WithdrawTooLarge exception

```
Thread 1
int b = getBalance();
if(amount > getBalance())
    throw new ...;
setBalance(b - amount);
```

```
Thread 2
int b = getBalance();
if(amount > getBalance())
    throw new ...;
setBalance(b - amount);
```
Still a bad fix, Another bad interleaving

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

- Assume initial balance 150
- This **should** cause a **WithdrawTooLarge** exception

---

Thread 1

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

Thread 2

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

---

In all 3 of these examples, instead of an exception, we have a “Lost withdraw”
Incorrect “fix”

It is tempting and almost always wrong to fix a bad interleaving by rearranging or repeating operations, such as:

```java
void withdraw(int amount) {
    if (amount > getBalance())
        throw new WithdrawTooLargeException();
    // maybe balance changed
    setBalance(getBalance() - amount);
}
```

This fixes nothing!

- Narrows the problem by one statement
- (Not even that since the compiler could turn it back into the old version because you didn’t indicate need to synchronize)
- And now a negative balance is possible — why?
What we want: Mutual exclusion

The fix: Allow at most one thread to withdraw from account A at a time
  – Exclude other simultaneous operations on A too (e.g., deposit)

Called mutual exclusion:
  • One thread using a resource (here: a bank account) means another thread must wait
  • We call the area of code that we want to have mutual exclusion (only one thread can be there at a time) a critical section.

Programmer (you!) must implement critical sections:
  – “The compiler” has no idea what interleavings should or should not be allowed in your program
  – But you need language primitives to do it!
Why is this Wrong?

Why can’t we implement our own mutual-exclusion protocol?

- Say we tried to coordinate it ourselves using a boolean variable - 'busy'
- It’s technically possible under certain assumptions, but won’t work in real languages anyway

```java
class BankAccount {
    private int balance = 0;
    private boolean busy = false;
    void withdraw(int amount) {
        while(busy) { /* “spin-wait” */ }
        busy = true;
        int b = getBalance();
        if(amount > b)
            throw new WithdrawTooLargeException();
        setBalance(b - amount);
        busy = false;
    }
    // deposit would spin on same boolean
}
```
Still just moved the problem!

Thread 1

```java
while(busy) { }

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

Thread 2

```java
while(busy) { }

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

"Lost withdraw" - unhappy bank

Time elapses between checking `busy` and setting `busy = true`
A thread can be interrupted there, allowing another thread to "sneak in".

Busy is initially = false
What we need

There are many ways out of this conundrum, but we need help from the programming language...

One solution: **Mutual-Exclusion Locks** (aka Mutex, or just Lock)
- Still on a conceptual level at the moment, 'Lock' is not a Java class (though Java's approach is similar)

We will 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" [all at once!]
  - Checking & setting happen together, and cannot be interrupted
  - Fixes problem we saw before!!
- **release**: makes this lock "not held"
  - If >= 1 threads are blocked on it, exactly 1 will acquire it
Why that works

- A **Lock** ADT with operations **new, acquire, release**

- The lock implementation ensures that given simultaneous acquires and/or releases, a correct thing will happen
  - Example:
    - If we have two acquires: one will “win” and one will block

- How can this be implemented?
  - Need to “check if held and if not make held” “all-at-once”
  - Uses special hardware and O/S support
    - See computer-architecture or operating-systems course
  - In CSE 332, we take this as a primitive and use it
Almost-correct pseudocode

```java
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
}
```

Note: ‘Lock’ is not an actual Java class
Some mistakes

• A lock is a very primitive mechanism
  – Still up to you to use correctly to implement critical sections

• Incorrect: Use different locks for withdraw and deposit
  – Mutual exclusion works only when using same lock
  – balance field is the shared resource being protected

• Poor performance: Use same lock for every bank account
  – No simultaneous operations on different accounts

• Incorrect: Forget to release a lock (blocks other threads forever!)
  – Previous slide is wrong because of the exception possibility!

```java
if(amount > b) {
    lk.release(); // hard to remember!
    throw new WithdrawTooLargeException();
}
```
Other operations

• If `withdraw` and `deposit` use the same lock, then simultaneous calls to these methods are properly synchronized.

• But what about `getBalance` and `setBalance`?
  – Assume they are public, which may be reasonable.

• If they do not acquire the same lock, then a race between `setBalance` and `withdraw` could produce a wrong result.

• If they do acquire the same lock, then `withdraw` would block forever because it tries to acquire a lock it already has!
One (not very good) possibility

```java
int setBalance1(int x) {
    balance = x;
}
int setBalance2(int x) {
    lk.acquire();
    balance = x;
    lk.release();
}
void withdraw(int amount) {
    lk.acquire();
    ...
    setBalance1(b - amount);
    lk.release();
}
Have two versions of setBalance!
- withdraw calls setBalance1 (since it already has the lock)
- Outside world calls setBalance2
- Could work (if adhered to), but not good style; also not very convenient

- Alternately, we can modify the meaning of the Lock ADT to support re-entrant locks
  - Java does this
  - Then just always use setBalance2
```
Re-entrant lock idea

A re-entrant lock (a.k.a. recursive lock)

- **The idea:** Once acquired, the lock is held by the Thread, and subsequent calls to acquire *in that Thread* won't block

- **Result:** withdraw can acquire the lock, and then call setBalance, which can also acquire the lock
  - Because they're in the same thread & it's a re-entrant lock, the inner acquire won't block!!
Re-entrant lock

A re-entrant lock (a.k.a. recursive lock)

- “Remembers”
  - the thread (if any) that currently holds it
  - a count

- When the lock goes from not-held to held, the count is set to 0

- If (code running in) the current holder calls acquire:
  - it does not block
  - it increments the count

- On release:
  - if the count is > 0, the count is decremented
  - if the count is 0, the lock becomes not-held
Re-entrant locks work

```c
int setBalance(int x) {
    lk.acquire();
    balance = x;
    lk.release();
}

void withdraw(int amount) {
    lk.acquire();
    ...
    setBalance(b - amount);
    lk.release();
}
```

This simple code works fine provided `lk` is a reentrant lock

- Okay to call `setBalance` directly
- Okay to call `withdraw` (won't block forever)
Java’s Re-entrant Lock

- `java.util.concurrent.locks.ReentrantLock`
- Has methods `lock()` and `unlock()`
- As described above, it is conceptually owned by the Thread, and shared within that thread
- Important to guarantee that lock is *always* released!!!
- Recommend something like this:
  ```java
  myLock.lock();
  try {
    // method body
  }
  finally {
    myLock.unlock();
  }
  ```
- Despite what happens in ‘try’, the code in finally will execute afterwards
**Synchronized: A Java convenience**

Java has built-in support for re-entrant locks
- You can use the `synchronized` statement as an alternative to declaring a `ReentrantLock`

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

1. Evaluates `expression` to an `object`
   - Every `object` (but not primitive types) “is 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!
Java version #1 (correct but can be improved)

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)
}
Improving the Java

- As written, the lock is **private**
  - Might seem like a good idea
  - But also prevents code in other classes from writing operations that synchronize with the account operations

- More idiomatic is to synchronize on **this**...
  - Also more convenient: no need to have an extra object!
class BankAccount {
    private int balance = 0;
    int getBalance() {
        synchronized (this) {
            return balance;
        }
    }
    void setBalance(int x) {
        synchronized (this) {
            balance = x;
        }
    }
    void withdraw(int amount) {
        synchronized (this) {
            int b = getBalance();
            if (amount > b)
                throw ...
            setBalance(b - amount);
        }
    }
    // deposit would also use synchronized(this)
}
**Syntactic sugar**

Version #2 is slightly poor style because there is a shorter way to say the same thing:

Putting `synchronized` before a method declaration means the entire method body is surrounded by

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

Therefore, version #3 (next slide) means exactly the same thing as version #2 but is more concise.
Java version #3 (final version)

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
}
More Java notes

- Class `java.util.concurrent.locks.ReentrantLock` works much more like our pseudocode
  - Often use `try { ... } finally { ... }` to avoid forgetting to release the lock if there’s an exception

- Also library and/or language support for readers/writer locks and condition variables (see Grossman notes)

- 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

1/14/2016 39
What could happen in this code?

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

- Assume initial balance 150

Thread 1

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

Thread 2

```java
int b = getBalance();
if(amount > getBalance())
    throw new ...
setBalance(getBalance() - amount);
```
Which of the following outcomes are possible given that we have 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) {
        if(amount > getBalance())
            throw new WithdrawTooLargeException();
        setBalance(getBalance() - amount);
    }
    ...
    // other operations like deposit, etc.
}
```

a) balance = -50
b) balance = 50
c) balance = 50, and one thread throws an exception
d) balance = 150
e) balance = -50, and one thread throws an exception