CSE 332 Autumn 2024
Lecture 23: Concurrency

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Memory Sharing With ForkJoin

- Idea of ForkJoin:
  - Reduce span by having many parallel tasks
  - Each task is responsible for **its own portion** of the input/output
  - If one task needs another's result, use join() to ensure it uses the final answer
- This does not help when:
  - Memory accessed by threads is overlapping or unpredictable
  - Threads are doing independent tasks using same resources (rather than implementing the same algorithm)

Example: Shared Queue

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

Imagine two threads are both using the same linked list based queue.

What could go wrong?

Concurrent Programming

- Concurrency:
  - Correctly and efficiently managing access to shared resources across multiple possibly-simultaneous tasks
- Requires synchronization to avoid incorrect simultaneous access
  - Use some way of “blocking” other tasks from using a resource when another modifies it or makes decisions based on its state
  - That blocking task will free up the resource when it’s done
- Warning:
  - Because we have no control over when threads are scheduled by the OS, even correct implementations are highly non-deterministic
  - Errors are hard to reproduce, which complicates debugging

Bank Account Example

- The following code implements a bank account object correctly for a synchronized situation
- Assume the initial balance is 150

```
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.
}
```

What Happens here?

```
withdraw(100);
withdraw(75)
```

Bank Account Example - Parallel

- Assume the initial balance is 150

```
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:

```
withdraw(100);
```

Thread 2:

```
withdraw(75);
```

Interleaving

- Due to time slicing, a thread can be interrupted at any time
  - Between any two lines of code
  - Within a single line of code
- The sequence that operations occur across two threads is called an interleaving
- Without doing anything else, we have no control over how different threads might be interleaved

A “Good” Interleaving

- Assume the initial balance is 150

Thread 1:	Thread 2:
withdraw(100);	withdraw(75);

	int b = getBalance();
	if (amount > b)
	throw new Exception();
	setBalance(b – amount);
int b = getBalance();	
if (amount > b)	
throw new Exception();	
setBalance(b – amount);	

A “Bad” Interleaving

- Assume the initial balance is 150

Thread 1:	Thread 2:
withdraw(100);	withdraw(75);

int b = getBalance();	

	int b = getBalance();
	if (amount > b)
	    throw new Exception();
	setBalance(b – amount);

if (amount > b)
    throw new Exception();
setBalance(b – amount);	

A Bad Fix

- Assume the initial balance is 150

```
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 still "Bad" Interleaving

- Assume the initial balance is 150

Thread 1:

```
withdraw(100);
```

Thread 2:

```
withdraw(75);
```

Thread 1	Thread 2
	if (amount > getBalance()) throw new Exception();

if (amount > getBalance())
    throw new Exception();
setBalance(getBalance() – amount);	

	setBalance(getBalance() – amount);
setBalance(getBalance() – amount);	

What we want – Mutual Exclusion

- While one thread is withdrawing from the account, we want to exclude all other threads from also withdrawing
- 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**.
- The programmer must implement critical sections!
  - It requires programming language primitives to do correctly

A Bad attempt at Mutual Exclusion

```
class BankAccount {
	private int balance = 0;
	private Boolean busy = false;
	int getBalance() { return balance; }
	void setBalance(int x) { balance = x; }
	void withdraw(int amount) {
		while (busy) { /* wait until not busy */ }
		busy = true;
		int b = getBalance();
		if (amount > b)
			throw new WithdrawTooLargeException();
		setBalance(b – amount);
		busy = false;}
	// other operations like deposit, etc.
}
```

A still "Bad" Interleaving

- Assume the initial balance is 150

Thread 1:	Thread 2:
withdraw(100);	withdraw(75);

```
Thread 1:
while (busy) { /* wait until not busy */ }

busy = true;

int b = getBalance();

                                    Thread 2:
                                    while (busy) { /* wait until not busy */ }

                                    busy = true;

                                    int b = getBalance();
                                    if (amount > b)
                                            throw new Exception();
                                    setBalance(b – amount);
                                    busy = false;

if (amount > b)
        throw new Exception();
setBalance(b – amount);
busy = false;
```

Solution

- We need a construct from Java to do this
- One Solution – A **Mutual Exclusion Lock** (called a Mutex or Lock)
- We define a **Lock** to be a ADT with operations:
  - New:
    - make a new lock, initially “not held”
  - Acquire:
    - If lock is not held, mark it as “held”
      - These two steps always done together in a way that cannot be interrupted!
    - If lock is held, pause until it is marked as “not held”
  - Release:
    - Mark the lock as “not held”

Almost Correct Bank Account Example

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

Questions:

1. What is the critical section?
2. What is the Error?

Try…Finally

- Try Block:
  - Body of code that will be run
- Finally Block:
  - Always runs once the program exits try block (whether due to a return, exception, anything!)

Correct (but not Java) Bank Account Example

```
class BankAccount {
        private int balance = 0;
        private Lock lck = new Lock();
        int getBalance() { return balance; }
        void setBalance(int x) { balance = x; }
        void withdraw(int amount) {
                try{
                        lk.acquire();
                        int b = getBalance();
                        if (amount > b)
                                throw new WithdrawTooLargeException();
                        setBalance(b – amount); }
                finally { lk.release(); } }
        // other operations like deposit, etc.
}
```

Questions:

1. Should deposit have its own lock object, or the same one?
2. What about getBalance?
3. What about setBalance?

A still "Bad" Interleaving

- Assume the initial balance is 150

Thread 1:

```
withdraw(100);
```

Thread 2:

```
if(getBalance()<75)
        setBalance(75);
```

```
try{
        lk.acquire();
        int b = getBalance();
        if (amount > b)
                throw new Exception();
                                              if(getBalance() < 75)
                                                      setBalance(75);
        setBalance(b – amount); }
finally { lk.release(); }
```

What's wrong here…

```
class BankAccount {
	private int balance = 0;
	private Lock lck = new Lock();
	int setBalance(int x) {
		try{
			lk.acquire();
			balance = x; }
		finally{ lk.release(); } }
	void withdraw(int amount) {
		try{
			lk.acquire();
			int b = getBalance();
			if (amount > b)
				throw new WithdrawTooLargeException();
			setBalance(b – amount); }
		finally { lk.release(); } }}
```

Withdraw calls setBalance!

Withdraw can never finish because in setBalance the lock will always be held!

Re-entrant Lock (Recursive Lock)

- Idea:
  - Once a thread has acquired a lock, future calls to acquire on the same lock will not block progress
- If the lock used in the previous slide is re-entrant, then it will work!

Re-entrant Lock Details

- A re-entrant lock (a.k.a. recursive lock)
- “Remembers”
  - the thread (if any) that currently holds it
  - a count of “layers” that the thread holds it
- 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

Java’s Re-entrant Lock Class

- java.util.concurrent.locks.ReentrantLock
- Has methods lock() and unlock()
- Important to guarantee that lock is always released!!!
- Recommend something like this:

```
myLock.lock();
try { // method body }
finally { myLock.unlock(); }
```

How this looks in Java

```
java.util.concurrent.locks.ReentrantLock;
class BankAccount {
        private int balance = 0;
        private ReentrantLock lck = new ReentrantLock();
        int setBalance(int x) {
                try{
                        lk.lock();
                        balance = x; }
                finally{ lk.unlock(); } }
        void withdraw(int amount) {
                try{
                        lk.lock();
                        int b = getBalance();
                        if (amount > b)
                                throw new WithdrawTooLargeException();
                        setBalance(b – amount); }
                finally { lk.unlock(); } }}
```

Java Synchronized Keyword

- Syntactic sugar for re-entrant locks
- You can use the synchronized statement as an alternative to declaring a ReentrantLock
- Syntax:

```
synchronized( /* expression returning an Object */ ) {statements}
```

- Any Object can serve as a “lock”
  - Primitive types (e.g. int) cannot serve as a lock
- Acquires a lock and blocks if necessary
  - Once you get past the “{“, you have the lock
- Released the lock when you pass “}”
  - Even in the cases of returning, exceptions, anything!
  - Impossible to forget to release the lock

Back Account Using Synchronize (Attempt 1)

```
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 new Exception();
                        setBalance(b – amount); } } // deposit would also use synchronized(lk)
}
```

Back Account Using Synchronize (Attempt 2)

```
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 new Exception();
                        setBalance(b – amount); } } // deposit would also use synchronized(lk)
}
```

Since we have one lock per account regardless of operation, it's more intuitive to use the account object itself as the lock!

More Syntactic Sugar!

- Using the object itself as a lock is common enough that Java has convenient syntax for that as well!
- Declaring a method as “**synchronized**” puts its body into a synchronized block with “this” as the lock

Back Account Using Synchronize (Final)

```
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 new WithdrawTooLargeException();
		setBalance(b – amount); }
	// other operations like deposit (which would use synchronized)
}
```

Race Condition

- Occurs when the computation result depends on scheduling (how threads are interleaved)
  - We, as programmers can't influence scheduling of threads
  - We need to write programs that work independent of scheduling
  - E.g.: if two threads are withdrawing, different schedules could cause different threads to see the WithdrawTooLargeException
- Data Race:
  - When there is the potential for two threads to be writing a variable in parallel
  - When there is the potential for one thread to be reading a variable while another writes to it
  - E.g.: Two threads insert the same into a hash table. The second thread in the schedule will overwrite the insert from the first.
- Bad Interleaving:
  - A race condition other than a data race
  - Usually it looks like exposing a "bad" intermediate state
  - E.g.: Two threads insert into a hash table. We compute the index for each key, then one thread resizes the table, now the other index might be incorrect.

Example: Shared Stack (no problems so far)

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

Critical sections of this code?

Race Condition, but no Data Race

```
class Stack {
        private E[] array = (E[])new Object[SIZE];
        private int index = -1;
        synchronized boolean isEmpty() { … }
        synchronized void push(E val) { … }
        synchronized E pop() { … }
        E peek(){
                E ans = pop();
                push(ans);
                return ans;
        }
}
```

Critical sections of this code?

Race Condition, including a Data Race

```
class Stack {
	private E[] array = (E[])new Object[SIZE];
	private int index = -1;
	synchronized boolean isEmpty() { … }
	synchronized void push(E val) { … }
	synchronized E pop() { … }
	E peek(){
		System.out.println(index);
		E ans = pop();
		push(ans);
		return ans;
	}
}
```

Peek and isEmpty

Expected Behavior:
Thread 2 should not see an empty stack if there is a push but no pop.

Thread 1:

```
peek();
```

Thread 2:

```
push(x);
boolean b = isEmpty();
```

E ans = pop();	push(x);
	boolean b = isEmpty();
push(ans);	
return ans;	

Peek and Push

Expected Behavior:
Thread 2 items from a stack are popped in LIFO order

Thread 1:

```
peek();
```

Thread 2:

```
push(x);
push(y);
System.out.println(pop());
System.out.println(pop());
```

E ans = pop();
push(ans);
return ans;
	push(x);
	push(y);
	System.out.println(pop());
	System.out.println(pop());

Peek and Push

Expected Behavior:
Thread 2 items from a stack are popped in LIFO order

Thread 1:

```
peek();
```

Thread 2:

```
push(x);
push(y);
System.out.println(pop());
System.out.println(pop());
```

Thread 1	Thread 2
	push(x);
E ans = pop();	
	push(y);
push(ans);	
return ans;	
	System.out.println(pop());
	System.out.println(pop());

How to fix this?

Make a bigger critical section

```
class Stack {
	private E[] array = (E[])new Object[SIZE];
	private int index = -1;
	synchronized boolean isEmpty() { … }
	synchronized void push(E val) { … }
	synchronized E pop() { … }
	E peek(){
		E ans = pop();
		push(ans);
		return ans;
	}
}
```

How to fix this?

Make a bigger critical section

```
class Stack {
        private E[] array = (E[])new Object[SIZE];
        private int index = -1;
        synchronized boolean isEmpty() { … }
        synchronized void push(E val) { … }
        synchronized E pop() { … }
        synchronized E peek(){
                E ans = pop();
                push(ans);
                return ans;
        }
}
```

Did this fix it?

No! Now it has a data race!

```
class Stack {
    private E[] array = (E[])new Object[SIZE];
    private int index = -1;
    synchronized boolean isEmpty() { … }
    synchronized void push(E val) { … }
    synchronized E pop() { … }
    E peek(){
        return array[index];
    }
}
```

Parallel Code Conventional Wisdom

Memory Categories

All memory must fit one of three categories:

1. Thread Local: Each thread has its own copy
2. Shared and Immutable: There is just one copy, but nothing will ever write to it
3. Shared and Mutable: There is just one copy, it may change
   - Requires Synchronization!

Thread Local Memory

- Whenever possible, avoid sharing resources
- Dodges all race conditions, since no other threads can touch it!
  - No synchronization necessary! (Remember Ahmdal's law)
- Use whenever threads do not need to communicate using the resource
  - E.g., each thread should have its on Random object
- In most cases, most objects should be in this category

Immutable Objects

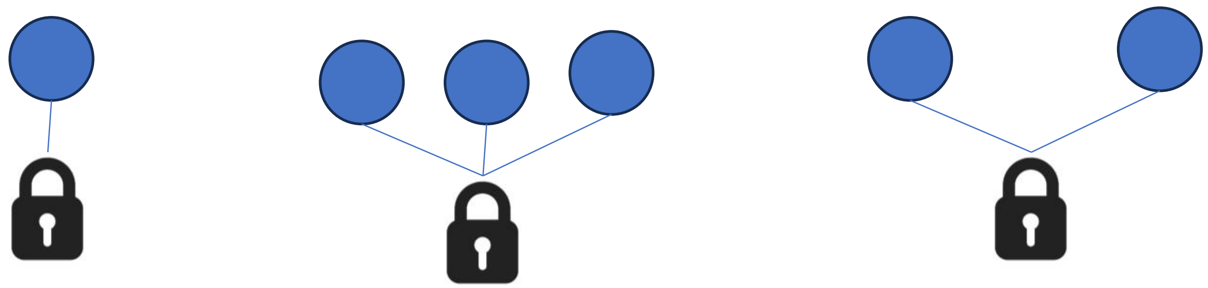
- Whenever possible, avoid changing objects
  - Make new objects instead
- Parallel reads are not data races
  - If an object is never written to, no synchronization necessary!
- Many programmers over-use mutation, minimize it

Shared and Mutable Objects

- For everything else, use locks
- Avoid all data races
  - Every read and write should be projected with a lock, even if it “seems safe”
  - Almost every Java/C program with a data race is wrong
- Even without data races, it still may be incorrect
  - Watch for bad interleavings as well!

Consistent Locking

- For each location needing synchronization, have a lock that is always held when reading or writing the location
- The same lock can (and often should) “guard” multiple fields/objects
  - Clearly document what each lock guards!
  - In Java, the lock should usually be the object itself (i.e. “this”)
- Have a mapping between memory locations and lock objects and stick to it!



Lock Granularity

- Coarse Grained: Fewer locks guarding more things each
  - One lock for an entire data structure
  - One lock shared by multiple objects (e.g. one lock for all bank accounts)
- Fine Grained: More locks guarding fewer things each
  - One lock per data structure location (e.g. array index)
  - One lock per object or per field in one object (e.g. one lock for each account)
- Note: there’s really a continuum between them…

Example: Separate Chaining Hashtable

- Coarse-grained: One lock for the entire hashtable
- Fine-grained: One lock for each bucket
- Which supports more parallelism in insert and find?
- Which makes rehashing easier?
- What happens if you want to have a size field?

Tradeoffs

- Coarse-Grained Locking:
  - Simpler to implement and avoid race conditions
  - Faster/easier to implement operations that access multiple locations (because all guarded by the same lock)
  - Much easier for operations that modify data-structure shape
- Fine-Grained Locking:
  - More simultaneous access (performance when coarse grained would lead to unnecessary blocking)
  - Can make multi-location operations more difficult: say, rotations in an AVL tree
- Guideline:
  - Start with coarse-grained, make finer only as necessary to improve performance

Similar But Separate Issue: Critical Section Granularity

- Coarse-grained
  - For every method that needs a lock, put the entire method body in a lock
- Fine-grained
  - Keep the lock only for the sections of code where it's necessary
- Guideline:
  - Try to structure code so that expensive operations (like I/O) can be done outside of your critical section
  - E.g., if you're trying to print all the values in a tree, maybe copy items into an array inside your critical section, then print the array's contents outside.

Atomicity

- Atomic: indivisible
- Atomic operation: one that should be thought of as a single step
- Some sequences of operations should behave as if they are one unit
  - Between two operations you may need to avoid exposing an intermediate state
  - Usually ADT operations should be atomic
    - You don’t want another thread trying to do an insert while another thread is rotating the AVL tree
- Think first in terms of what operations need to be atomic
  - Design critical sections and locking granularity based on these decisions

Use Pre-Tested Code

- Whenever possible, use built-in libraries!
- Other people have already invested tons of effort into making things both efficient and correct, use their work when you can!
  - Especially true for concurrent data structures
  - Use thread-safe data structures when available
    - E.g. Java as ConcurrentHashMap

Deadlock

- Occurs when two or more threads are mutually blocking each other
- T1 is blocked by T2, which is blocked by T3, …, Tn is blocked by T1
  - A cycle of blocking

Bank Account

```
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);
	}
}
```

The Deadlock

Expected Behavior:
Thread 2 items from a stack are popped in LIFO order

Thread 1:

```
x.transferTo(1,y);
```

Thread 2:

```
y.transferTo(1,x);
```

acquire lock for account x b/c transferTo is synchronized **acquire lock for account y** b/c deposit is synchronized **release lock for account y** after depost **release lock for account x** at end of transferTo	**acquire lock for account y** b/c transferTo is synchronized **acquire lock for account x** b/c deposit is synchronized **release lock for account x** after deposit **release lock for account y** at end of transferTo

The Deadlock

Expected Behavior:
Thread 2 items from a stack are popped in LIFO order

Thread 1:

```
x.transferTo(1,y);
```

Thread 2:

```
y.transferTo(1,x);
```

acquire lock for account x b/c transferTo is synchronized **acquire lock for account y** b/c deposit is synchronized **release lock for account y** after depost **release lock for account x** at end of transferTo	**acquire lock for account y** b/c transferTo is synchronized **acquire lock for account x** b/c deposit is synchronized **release lock for account x** after deposit **release lock for account y** at end of transferTo

Resolving Deadlocks

- Deadlocks occur when there are multiple locks necessary to complete a task and different threads may obtain them in a different order
- Option 1:
  - Have a coarser lock granularity
  - E.g. one lock for ALL bank accounts
- Option 2:
  - Have a finer critical section so that only one lock is needed at a time
  - E.g. instead of a synchronized transferTo, have the withdraw and deposit steps locked separately
- Option 3:
  - Force the threads to always acquire the locks in the same order
  - E.g. make transferTo acquire both locks before doing either the withdraw or deposit, make sure both threads agree on the order to aquire

Option 1: Coarser Locking

```
static final Object BANK = new Object();
class BankAccount {
        …
        synchronized void withdraw(int amt) {…}
        synchronized void deposit(int amt) {…}
        void transferTo(int amt, BankAccount a) {
                synchronized(BANK){
                        this.withdraw(amt);
                        a.deposit(amt);
                }
        }
}
```

Option 2: Finer Critical Section

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

Option 3: First Get All Locks In A Fixed Order

```
class BankAccount {
        …
        synchronized void withdraw(int amt) {…}
        synchronized void deposit(int amt) {…}
        void transferTo(int amt, BankAccount a) {
                if (this.acctNum < a.acctNum){
                        synchronized(this){
                                synchronized(a){
                                        this.withdraw(amt);
                                        a.deposit(amt);
                } } }
                else {
                        synchronized(a){
                                synchronized(this){
                                        this.withdraw(amt);
                                        a.deposit(amt);
                } } }
        }
}
```