



CSE 332: Data Structures & Parallelism  
Lecture 17: Shared-Memory Concurrency &  
Mutual Exclusion

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## *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)

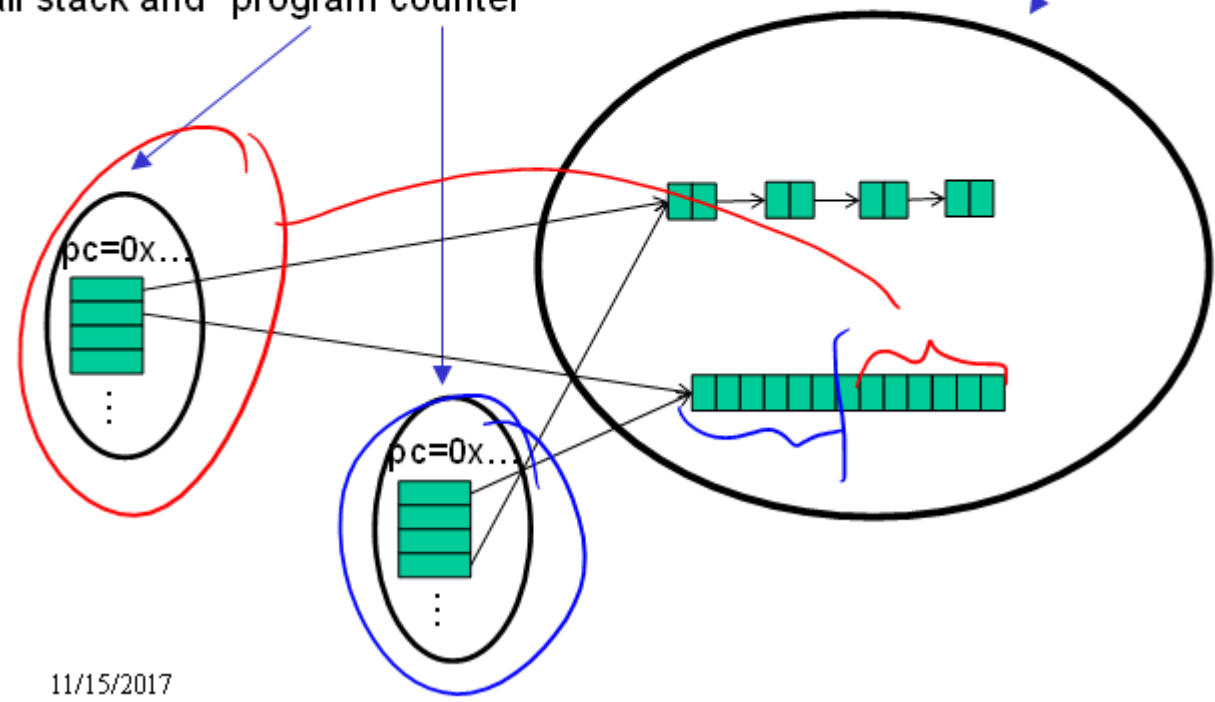
*Each thread accesses a different sub-range of the array: Array is shared, but no overlap*

```
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"

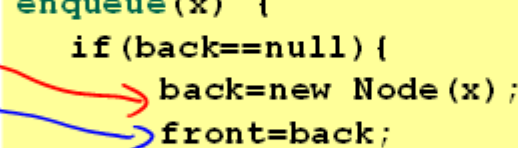
Heap for all objects and static fields, *shared* by all threads



## Sharing a Queue....

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

```
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)

```
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 enqueueer 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

```
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

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

Thread 2

```
x.withdraw(75);
```

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## Activity: A bad interleaving

Interleaved `withdraw()` calls on the same account

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

balance = ~~75~~  
50

Thread 1: `withdraw(100)`

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

getBalance()

getBalance()

b = 150

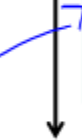
Thread 2: `withdraw(75)`

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

b = 150

⋮

Time

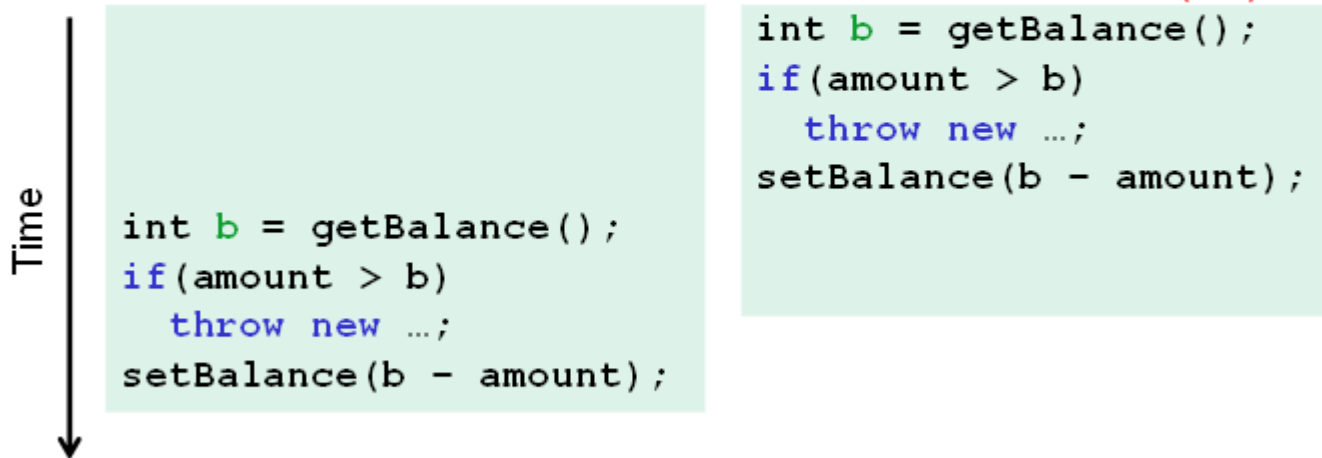


## Activity: A “good” execution is also possible

Interleaved `withdraw()` calls on the same account

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

Thread 1: `withdraw(100)`



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

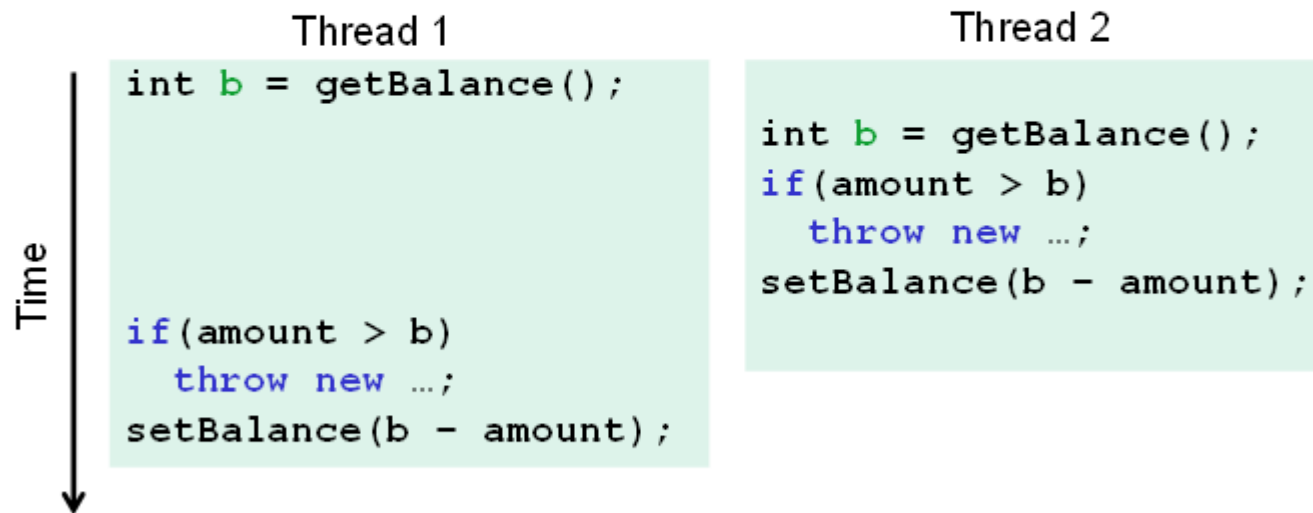
Thread 2: `withdraw(75)`

```
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

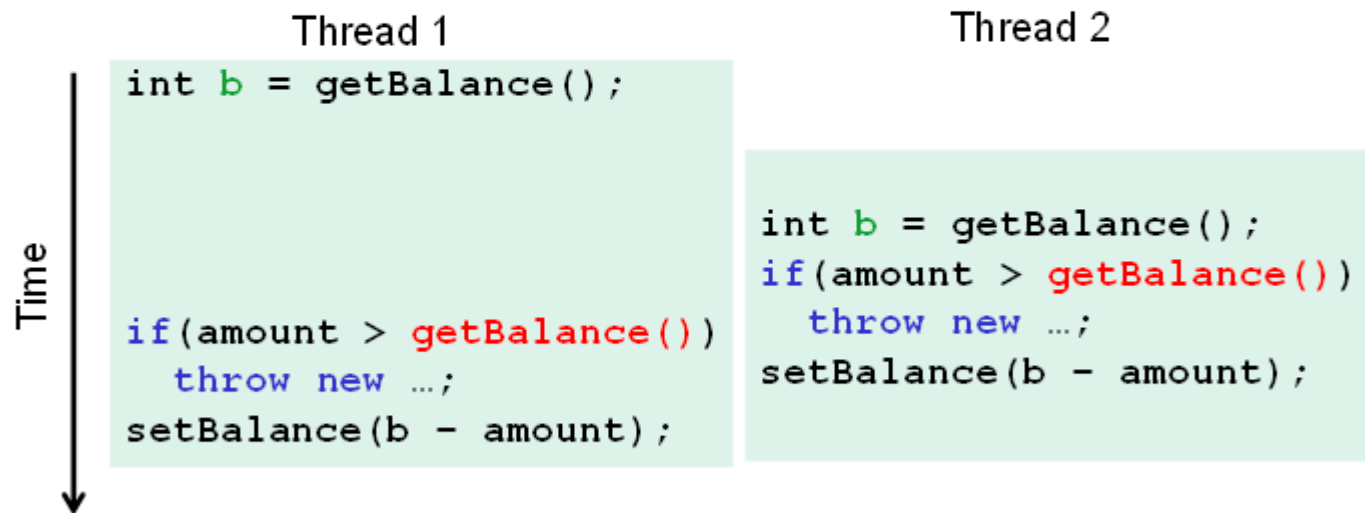




## A bad fix, Another bad interleaving

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

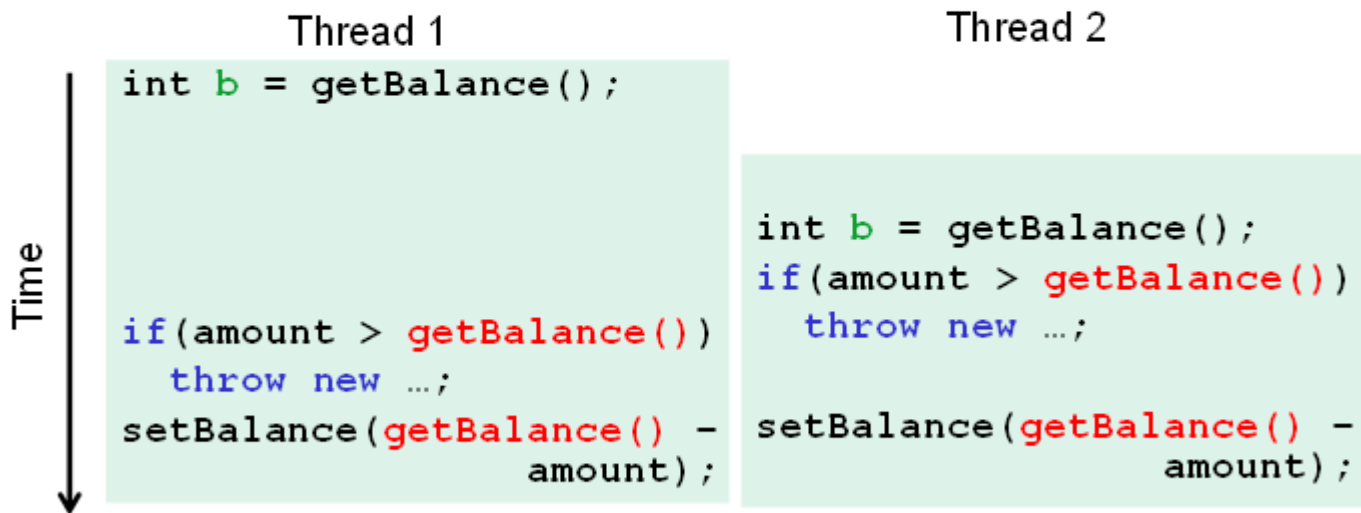
- Assume initial balance 150
- This *should* cause a `WithdrawTooLarge` exception



## 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



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:

```
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?

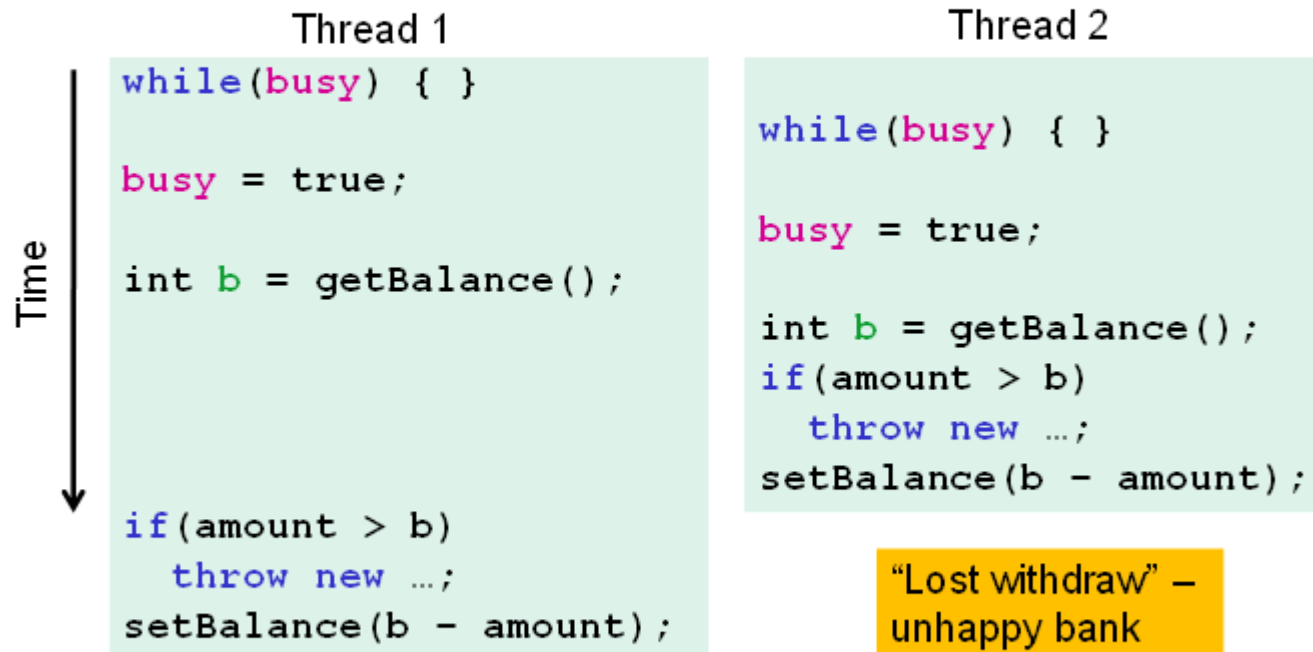
Why can't we implement our own mutual-exclusion protocol?

- 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

```
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
}
```

**Busy** is initially = false

## Still just moved the problem!



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


## 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  $\geq 1$  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



Note: 'Lock' is not an actual Java class

## Almost-correct pseudocode

```
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();
            lk.release();
        }
        setBalance(b - amount);
        lk.release();
    }
    // deposit would also acquire/release lk
}
```

## *Questions about the previous slide*

1. Where is the critical section?
2. How many locks do we need?
  - a) One lock per BankAccount object?
  - b) Two locks per BankAccount object? (one lock for withdraw and one lock for deposit)
  - c) One lock for the entire class?
3. There is a bug in withdraw(), can you find it?
4. Do we need locks for:
  - a) getBalance?
  - b) setBalance?

## 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!

```
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

```
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*

```
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:

```
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!

## Java version #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 ...
            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

```
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

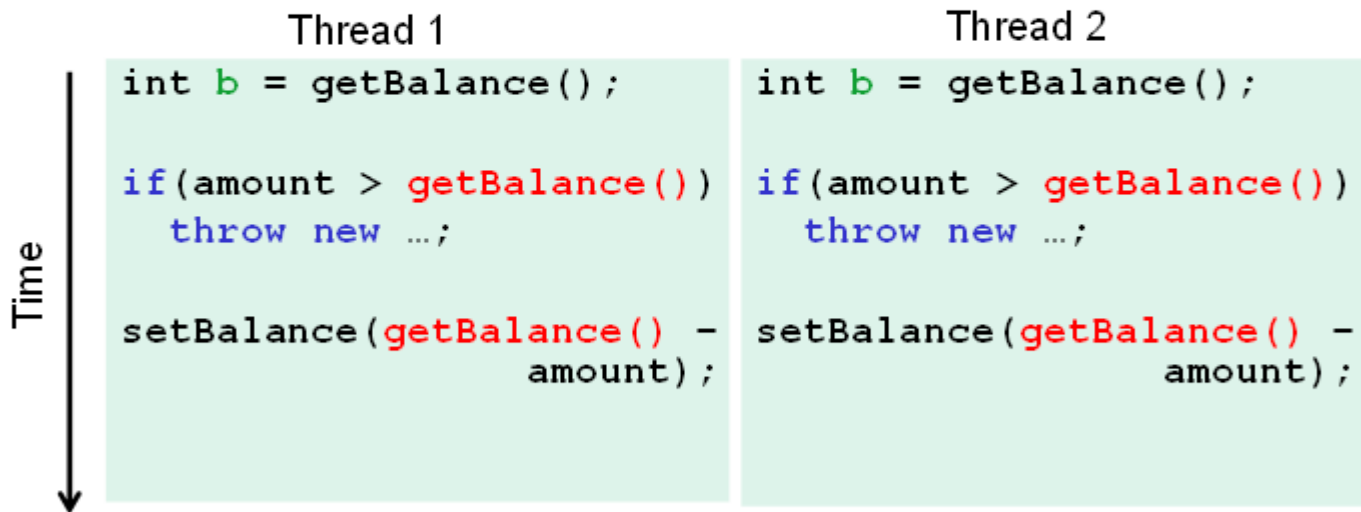
- Class `java.util.concurrent.locks.ReentrantLock` works much more like our pseudocode
  - Often use `try { ... } finally { ... }` to avoid forgetting to release the lock if there's an exception
- Also library and/or language support for *readers/writer locks* and *condition variables* (see Grossman 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



## What could happen in this code?

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

- Assume initial `balance` 150



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)

```
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