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

```
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);
```

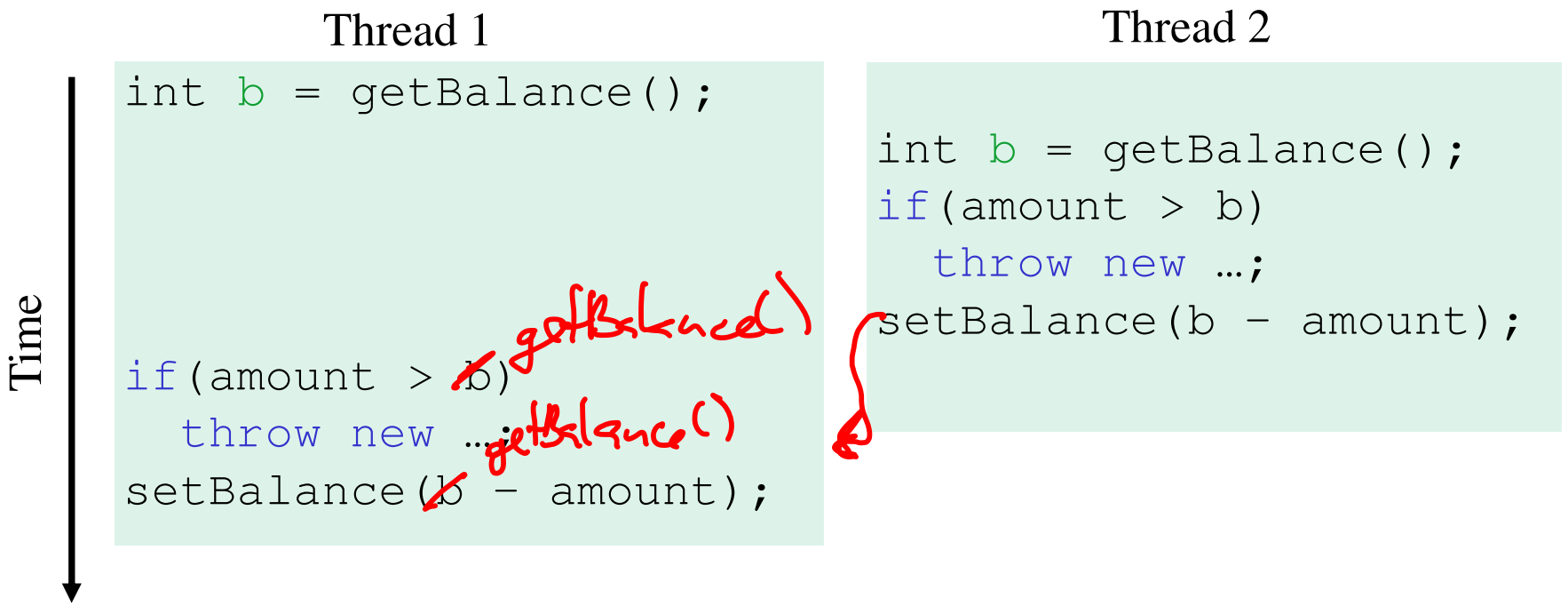
Thread 2

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

A bad interleaving

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

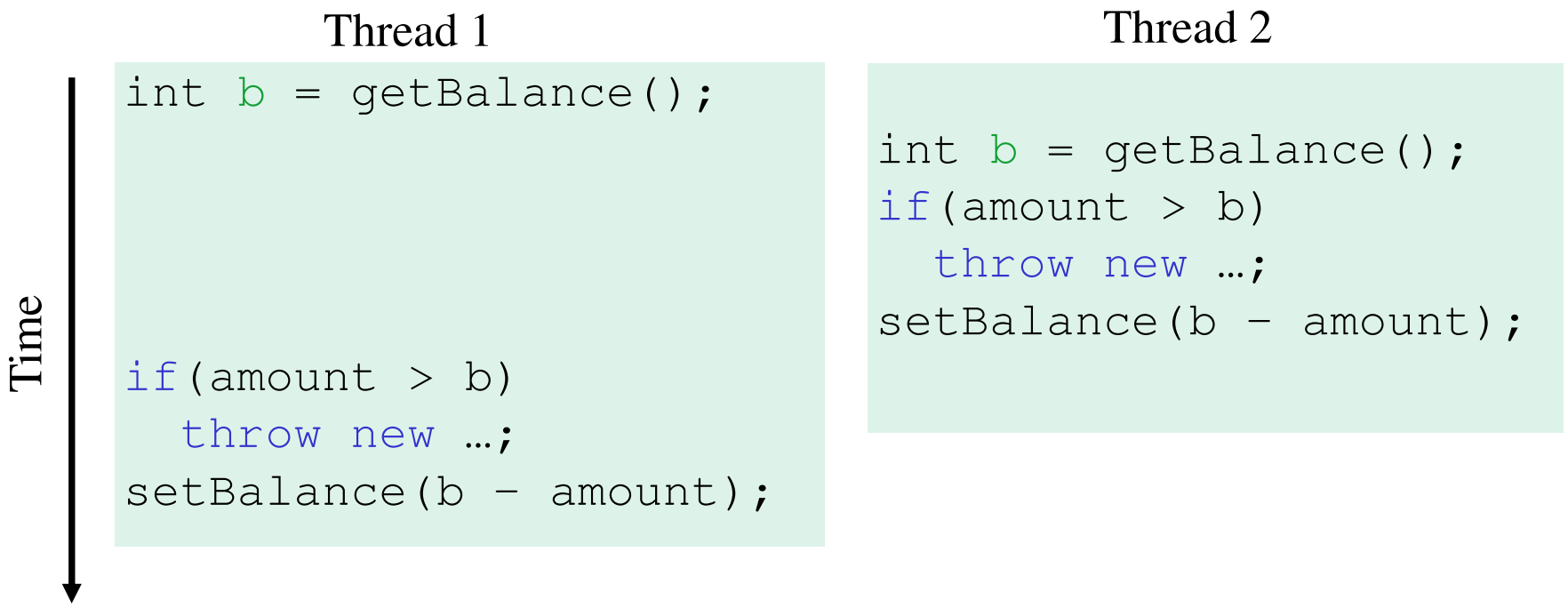
- Assume initial **balance == 150**



How to fix?

No way to fix by rewriting the program

- can always find a bad interleaving -> violation
- need some kind of synchronization



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~~ ordering 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 – transactions
- source control

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)

Lock ADT

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"* by someone else
  - 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

no two users can withdraw at same time even on different accounts!

- Too many locks
  - separate locks for deposit, withdraw

could have deposit & withdraw simultaneously

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

```
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

BankAccount in Java

```
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

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

This is so common that Java provides a shorthand:

```
synchronized {
  statements
}
```

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
}
```

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

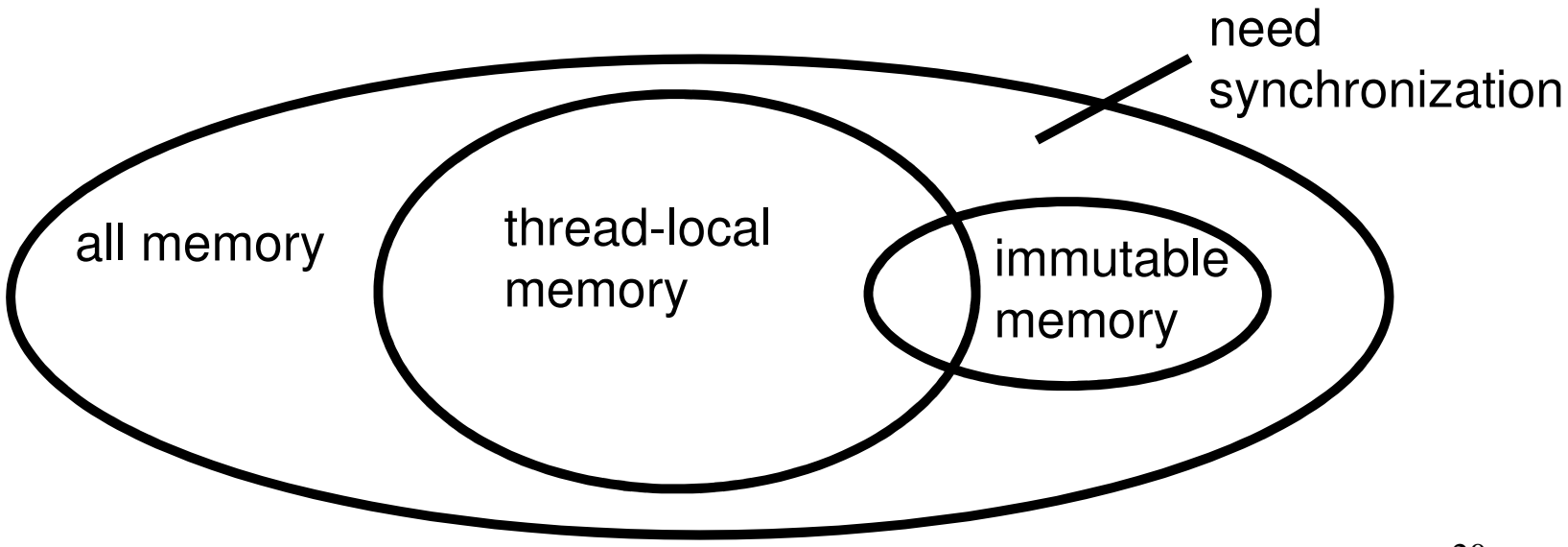
Stack Example (fixed)

```
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



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 synchronizatin 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