

Race Conditions

CSE 332 Summer 2021

Instructor: Kristofer Wong

Teaching Assistants:

Alena Dickmann	Arya GJ	Finn Johnson
Joon Chong	Kimi Locke	Peyton Rapo
Rahul Misal	Winston Jodjana	

Announcements

- ❖ 3 weeks left!!
- ❖ Confusion over gitlab turn in
 - Only needed to commit ex10 before the deadline (we'll be testing the last commit before the deadline)
 - Now realizing need to change to gradescope for 11/12
- ❖ Lecture Recordings
- ❖ P2 late turn in
- ❖ P3 test bug

Lecture Outline

- ❖ **Locks recap**
- ❖ Re-entrancy
- ❖ Locking in Java
- ❖ Race Conditions: Data Races vs. Bad Interleavings


Mutual Exclusion & Locking Recap

- ❖ Need Threads to synchronize: Want **Mutual Exclusion**
 - Only one thread should access some resources at one time
- ❖ The sections of code needing Mutual Exclusion: **Critical Sections**
- ❖ A **Lock** ADT with operations **new, acquire, release**
 - Only one executor may acquire an instance of the lock at one time
 - Given simultaneous acquires/releases, a “correct thing” will happen
 - Specifically: if we have two acquires: one will “win” and one will block
- ➔ Needs hardware and O/S support



Friday's Gradescope Questions

Answer the questions based on 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?
 - i.e., one for withdraw() and one for deposit()
 - c) One lock for the entire Bank
 - Bank contains multiple BankAccount instances
3.  There is a bug in withdraw(), can you find it?

Incorrect Bank Account Pseudocode

```
1  class BankAccount {
2      private int balance = 0;
3      private Lock lk = new Lock();
4
5      public void withdraw(int amount) {
6          lk.acquire(); // may block
7          int b = getBalance();
8          if (amount > b)
9              throw new WithdrawTooLargeException();
10         setBalance(b - amount);
11         lk.release();
12     }
13
14     // deposit() would also acquire/release lk
15 }
```

Note: 'Lock' is not an actual Java class

Answers: Some Common Locking Mistakes

- ❖ A lock is very primitive; up to you to use correctly
- ❖ **Incorrect**: different locks for **withdraw** and **deposit**
 - Mutual exclusion works only when sharing same lock
 - **balance** field is the shared resource being protected
- ❖ **Poor performance**: same lock for entire Bank
 - No simultaneous operations on *different* accounts
- ❖ **Bug**: forgot to release a lock when exiting early
 - Can block other threads forever if there's an exception

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

Remembering to release() before every exit is challenging!

Summary of Mutual Exclusion

- ❖ Threads are useful beyond just fork-join-style parallelism
 - But general use-cases require **concurrency** to ensure correctness when dealing with overlapped sharing
- ❖ Overlapped sharing introduces **non-determinism** because the system controls the scheduling of threads
 - Therefore, the system must also provide **locks** to ensure **mutual exclusion** in **critical sections** of code
 - Mutual exclusion is the technique we employ to prevent **bad interleavings**

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Adding Operations to Our BankAccount

- ❖ If **withdraw** and **deposit** use the same lock, then simultaneous calls to them are properly synchronized 🍷
- ❖ But what about **getBalance** and **setBalance**?
 - Assume now that 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

- ❖ Have two versions of setBalance!
 - withdraw() calls a non-locking version of setBalance() (since it already has the lock)
 - Outside world calls the locking version of setBalance()
- ❖ Could work if adhered to, but not good style
 - Also inconvenient
- ❖ Alternately, we can modify the meaning of the Lock ADT to support **re-entrant locks**
 - Java does this
 - Then just always use the locking version of setBalance()

```
private int setBalanceNoLock(  
    int x) {  
    balance = x;  
}  
  
→ public int setBalance(int x) {  
    lk.acquire();  
    setBalanceNoLock(x);  
    lk.release();  
}  
  
→ public void withdraw(int amount) {  
    lk.acquire();  
    ...  
    setBalanceNoLock(b - amount);  
    lk.release();  
}
```

Re-entrancy

- ❖ A **re-entrant lock** (a.k.a. **recursive lock**)
 - Once acquired, the lock is held *by the executor*,
 - Subsequent acquire calls *in that executor* won't block

- ❖ Example:
 - `withdraw()` can acquire the lock
 - Then, `withdraw()` can call `setBalance()`, which also acquires the lock
 - Because they're *in the same executor* and it's a *re-entrant* lock, the inner acquire won't block!

Re-entrant Lock Implementation

- ❖ Contains the following state:
 - the thread (if any) that currently holds it and a count
- ❖ When the lock goes from not-held to held:
 - remembers the thread and sets count = 0
- ❖ If the *current holder* calls acquire() again:
 - it does not block and count++
- ❖ If the *current holder* calls release():
 - if count > 0 and count--
 - if count == 0, the lock “forgets” the thread

held [T]
Count [0]

→ held [T]
Count [1]

Withdraw()

→ lock.acquire()
set

→ lock.release()

↳ held [T]
Count [1]

→ lock.acquire()
// set code
lock.release()

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- ❖ Race Conditions: Data Races vs. Bad Interleavings

Java's Re-entrant Lock

- ❖ Java doesn't have the "plain" lock we discussed earlier; it only has re-entrant locks
- ❖ `java.util.concurrent.locks.ReentrantLock`
 - Has methods lock() and unlock()

(lck.lock())
crit. ---
⋮
(lck.unlock())

Locking Best Practices in Java

- ❖ Remember our bug in withdraw()?
- ❖ Need to guarantee that locks are always released
 - Recommend something like this:

```
myLock.lock();
```

```
→ try { /* method body */ }
```

```
→ finally { myLock.unlock(); }
```

- The code in `finally` will always execute afterwards
 - Regardless of exceptions, returns, or “normal” completion

synchronized: A Java Convenience

- ❖ Or use `synchronized` statement instead of explicitly instantiating a `ReentrantLock` + try/catch/finally blocks

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

- ❖ `synchronized` statement:

- Evaluates *expression* to an object
 - Every object (but not primitive types) can be a lock in Java
- Acquires the lock, blocking if necessary
 - “If you get past the {, you have the lock”
- Releases the lock “at the matching }”, even if throw, return, etc.
 - So it’s impossible to forget to release the lock

Version #1: Correct, But Can Be Improved

```
class BankAccount {  
    private int balance = 0;  
    private Object lk = new Object();  
  
    protected int getBalance()  
        { synchronized (lk) { return balance; } }  
    protected void setBalance(int x)  
        { synchronized (lk) { balance = x; } }  
  
    public void withdraw(int amount) {  
        synchronized (lk) {  
            int b = getBalance();  
            if (amount > b)  
                throw ...  
            setBalance(b - amount);  
        }  
    }  
  
    // deposit() would also use synchronized(lk)  
}
```

Improving Version #1

❖ As written, the lock is **private**

- Seems like a good idea ... ?
- But prevents other classes from synchronizing with BankAccount operations

→ ❖ More idiomatic is to synchronize on **this**

- Also more convenient: no need to have an extra object!

Version #2: Still Improvable

```
class BankAccount {
    private int balance = 0;

    protected int getBalance()
    { synchronized (this){ return balance; } }
    protected void setBalance(int x)
    { synchronized (this){ balance = x; } }

    public void withdraw(int amount) {
        synchronized (this) {
            int b = getBalance();
            if(amount > b)
                throw ...
            setBalance(b - amount);
        }
    }

    // deposit() would also use synchronized(this)
}
```

Improving Version #2: Syntactic Sugar

- ❖ There is a shorter way to say the same thing as version #2
- ❖ Putting **synchronized** before a method declaration means the entire method body is surrounded by

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

- ❖ Version #3 is *identical to version #2*, but more concise, more standard, and therefore better style

Version #3: Final Version

```
class BankAccount {
    private int balance = 0;

    synchronized protected int getBalance()
    { return balance; }
    synchronized protected void setBalance(int x)
    { balance = x; }


    synchronized public void withdraw(int amount) {
        int b = getBalance();
        if (amount > b)
            throw ...
        setBalance(b - amount);
    }

    // deposit() would also use synchronized
}
```

code that is not critical

sure

A Few Final Thoughts

- ❖ Our `synchronized`-less `BankAccount` pseudocode needs `java.util.concurrent.locks.ReentrantLock` and `try { ... } finally { ... }` blocks
 - Or just used `synchronized` 😊

- ❖ Don't have time to cover these highly-relevant lock variants:
readers/writer locks and *condition variables*
 - ➔ See Grossman notes for more info
- ❖ Java provides many other features and details. See also:
 - Chapter 14 of *CoreJava, Volume 1* by Horstmann/Cornell
 - *Java Concurrency in Practice* by Goetz et al

Lecture Outline

- ❖ Locks recap
- ❖ Re-entrancy
- ❖ Locking in Java
- ❖ **Race Conditions: Data Races vs. Bad Interleavings**

Race Conditions

- ➔ A *race condition* occurs when the computation result depends on scheduling (ie, how threads are interleaved)
 - i.e.: if T1 and T2 are scheduled in a certain way, things go “wrong”
 - Only exist due to concurrency: no interleaving with only 1 thread!
- ❖ We, as programmers, cannot control scheduling of threads
 - Thus we must write programs that work independent of scheduling

Data Races vs. Bad Interleavings

- ❖ We will make a big distinction between:

data races and *bad interleavings*

- ❖ Both are types of *race conditions*
 - Confusion often results from not distinguishing these, or using the term “race condition” to refer to only one of these two

Very Briefly: Data Races

❖ A **data race** is a type of **race condition** that can happen when:

- Different threads **potentially** write a variable *at the same time*

- One thread **potentially** writes a variable *at the same time* another thread reads it

write/write X read/read ✓
write/read X

❖ Two threads *reading* the same variable at the same time is not a data race and doesn't create an error

- The key is that one of the threads must be *writing* to the variable

❖ The 'potentially' is important!

- Code has a data race independent of any particular actual execution

Bad Interleavings

- ❖ Easy to see why **data races** are bad
- ❖ However, we can still have a **race condition** (and bad behavior) even without **data races**, thanks to **bad interleavings**
 - Different threads' reads and writes are “interleaved” without simultaneity



- ❖ Warning sign: intermediate/temporary state visible to a concurrently executing thread
 - E.g.: partial insert in a linked list: ‘front’ field updated with new node, but ‘count’ not yet updated

Bad Interleavings: Canonical Example

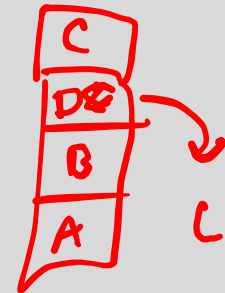
```
class Stack<E> {  
    private E[] array = (E[])new Object[SIZE];  
    private int index = -1;  
  
    synchronized public boolean isEmpty() {  
        return index == -1;  
    }  
    synchronized public void push(E val) {  
        array[++index] = val;  
    }  
    synchronized public E pop()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

A Race Condition but Not a Data Race

```
class Stack<E> {  
    // state used by isEmpty, push, pop  
  
    synchronized public boolean isEmpty() { ... }  
    synchronized public void push(E val) { ... }  
    synchronized public E pop() { ... }
```

```
    public E peek() { // this is wrong  
        → E ans = pop();  
        → push(ans);  
        return ans;  
    }  
}
```

T2



peek, Sequentially Speaking

- ❖ In a sequential world, this code is of questionable *style* but unquestionably *correct*
 - Imagine this is the only way to add peek functionality to an existing class or interface

```
interface Stack<E> {  
    boolean isEmpty();  
    void push(E val);  
    E pop();  
}  
  
class C {  
    public static <E> E myPeek(Stack<E> s) {  
        ...  
    }  
}
```

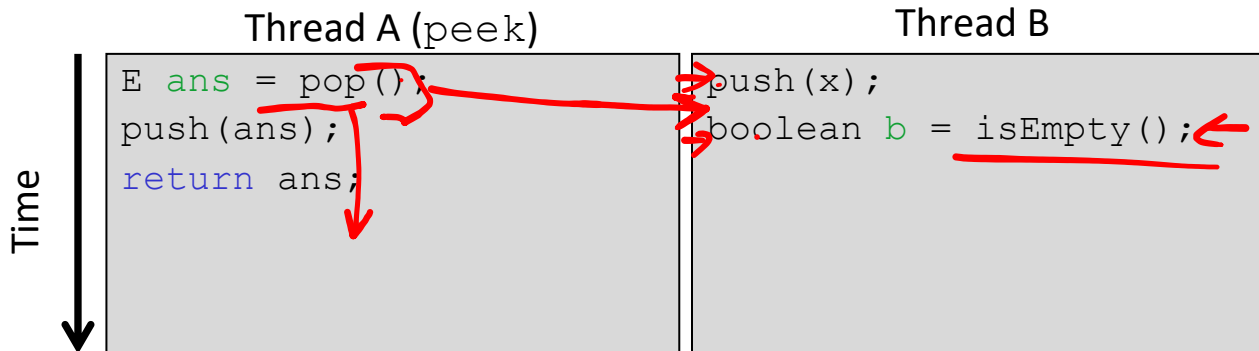
Concurrency Problems with peek

```
public E peek() {  
    E ans = pop();  
    push(ans);  
    return ans;  
}
```

- ❖ peek has no **overall** effect on the shared data
 - It is a “reader” not a “writer”; state should be the same before and after it executes
- ❖ peek’s calls to push and pop are synchronized
 - So there are no data races on the underlying array/index
✓
- ❖ But the way it is implemented creates a **race condition**
 - peek has an intermediate state that shouldn’t be exposed to other threads
 - If exposed to other threads, peek’s intermediate state can lead to bad interleavings

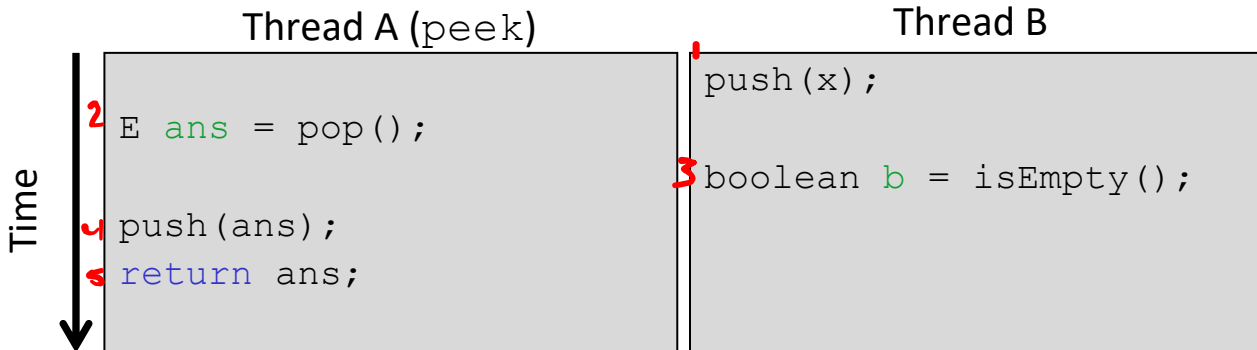
Bad Interleaving #1: peek and isEmpty

- ❖ **Property we want:** If there has been a push (and no pop), then isEmpty should return **false**
- ❖ With **peek** as written, property can be violated – how?



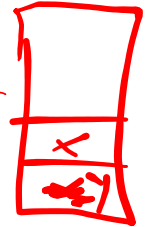
Answer #1: peek and isEmpty

- ❖ **Property we want:** If there has been a **push** (and no **pop**), then **isEmpty** should return **false**
- ❖ With **peek** as written, property can be violated – how?

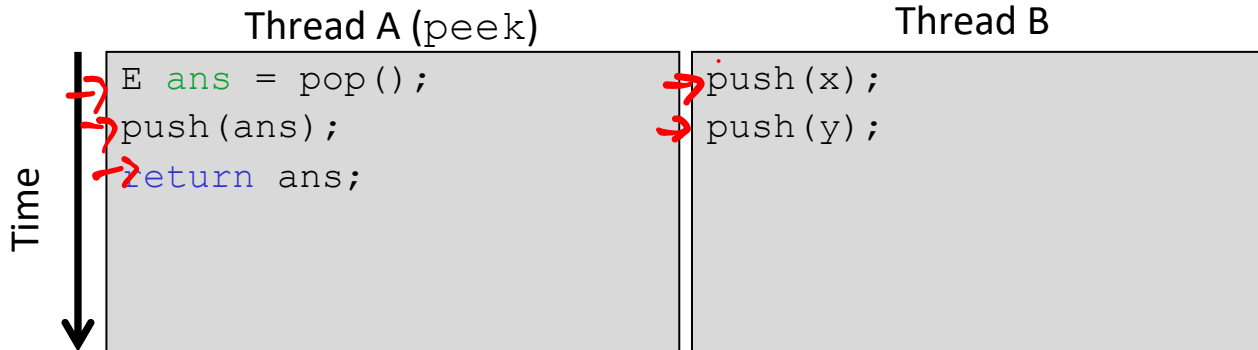


Bad Interleaving #2: peek and push

- ❖ **Property we want:** Values are push()'ed in LIFO order
- ❖ With **peek** as written, property can be violated – how?

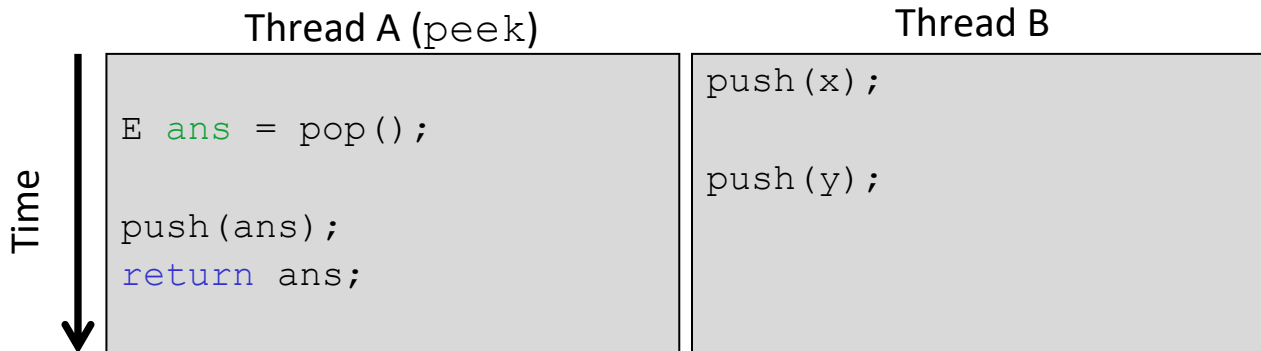


✗



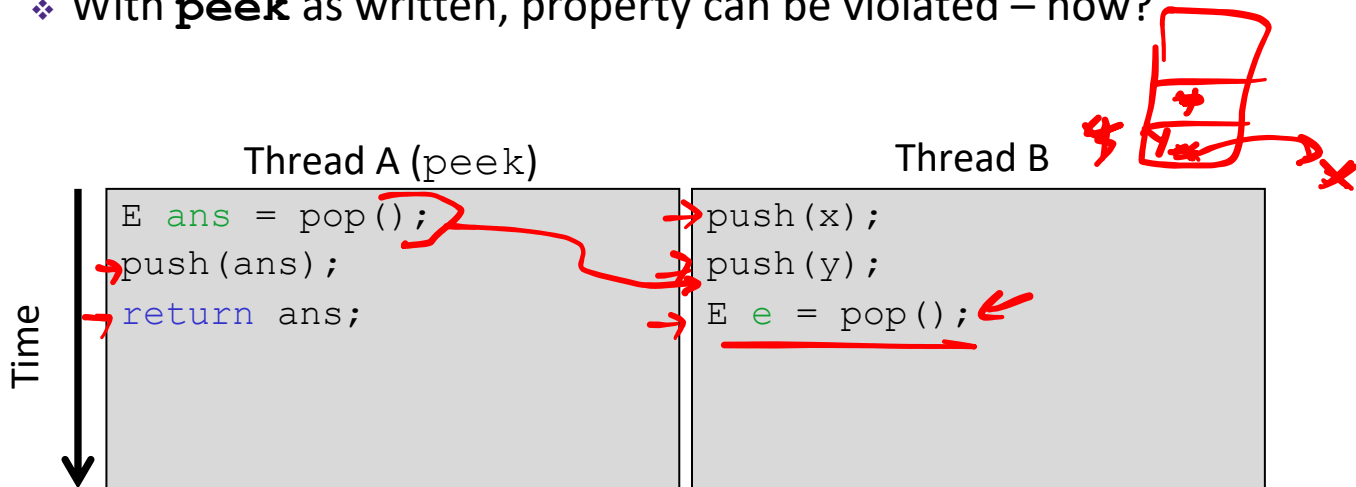
Answer #2: peek and push

- ❖ **Property we want:** Values are `push()`'ed in LIFO order
- ❖ With `peek` as written, property can be violated – how?



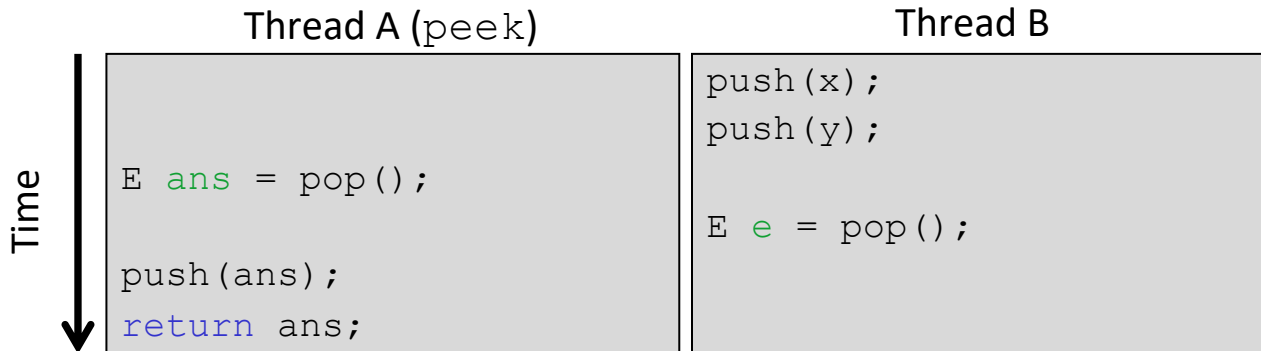
Bad Interleaving #3: peek and pop

- ❖ **Property we want:** Values are returned from **pop** in LIFO order
- ❖ With **peek** as written, property can be violated – how?

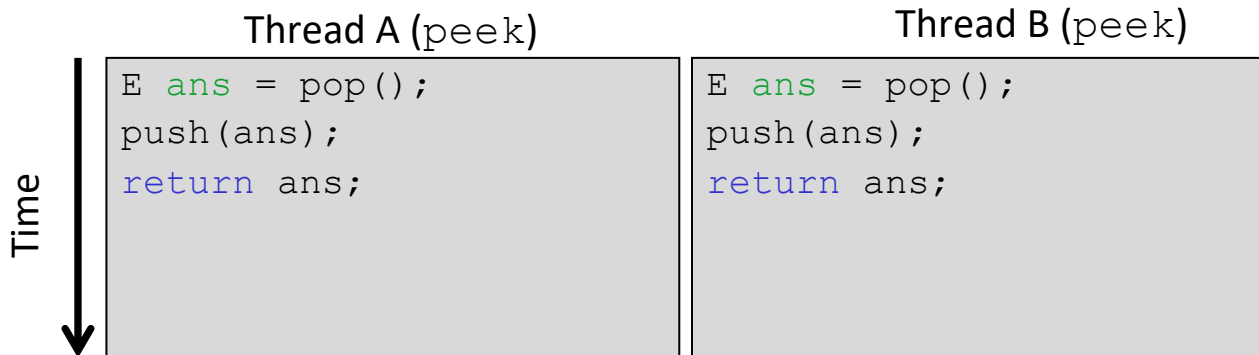


Answer #3: peek and pop

- ❖ **Property we want:** Values are returned from **pop** in LIFO order
- ❖ With **peek** as written, property can be violated – how?



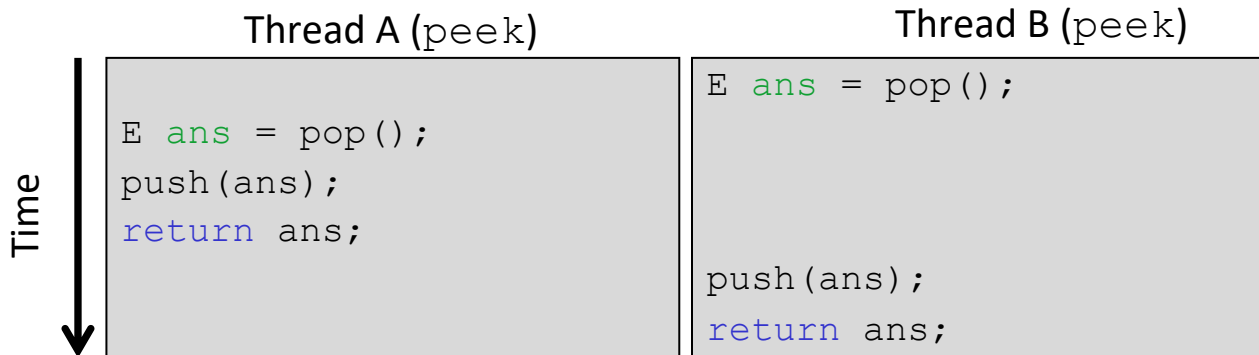
- ❖ **Property we want:** `peek` doesn't throw an exception unless stack is empty
- ❖ With `peek` as written, property can be violated – how?



Bad Interleaving #4: peek and peek

Answer #4: peek and peek

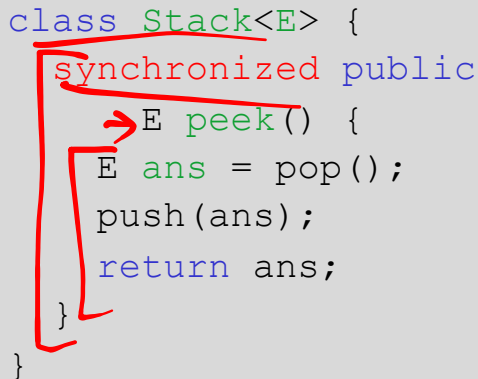
- ❖ **Property we want:** `peek` doesn't throw an exception unless stack is empty
- ❖ With `peek` as written, property can be violated – how?



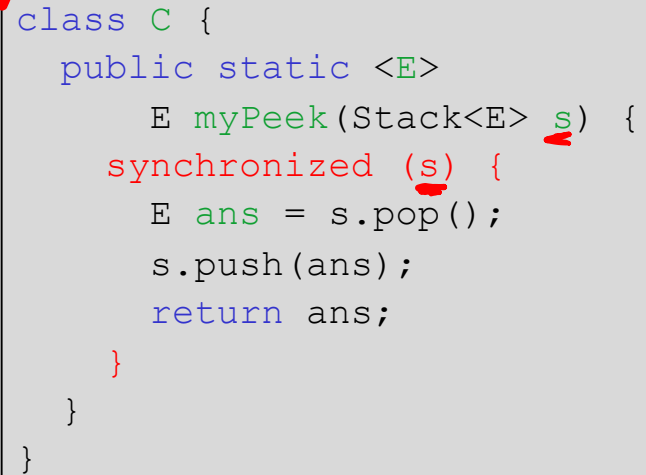
The Fix: Disallow Interleavings

- ❖ **peek** needs synchronization to disallow interleavings
 - *Enlarging the critical section* will protect `peek`'s intermediate state
 - Re-entrant locks will allow calls to **push** and **pop**
 - Code on right is example of a `peek` external to the `Stack` class

```
class Stack<E> {  
    synchronized public  
        E peek() {  
            E ans = pop();  
            push(ans);  
            return ans;  
        }  
}
```



```
class C {  
    public static <E>  
        E myPeek(Stack<E> s) {  
            synchronized (s) {  
                E ans = s.pop();  
                s.push(ans);  
                return ans;  
            }  
        }  
}
```



The Wrong “Fix”: Read-only Interleavings

- ❖ **Problem so far:** `peek` does writes which yield an incorrect intermediate state
- ➡ **Tempting but wrong:** if `peek` (or `isEmpty`) doesn't write anything, maybe we can skip the synchronization?
 - Unfortunately, does NOT work due to data races with push and pop

Turning a Bad Interleaving Into a Data Race

```
class Stack<E> {  
    private E[] array = (E[])new Object[SIZE];  
    private int index = -1;  
  
    public boolean isEmpty() { // unsynchronized; wrong?!  
        return index == -1;  
    }  
  
    synchronized public void push(E val) {  
        array[++index] = val;  
    }  
  
    synchronized public E pop() {  
        return array[index--];  
    }  
  
    public E peek() { // unsynchronized and wrong!  
        return array[index];  
    }  
}
```

Handwritten annotations:

- A red bracket underlines the `array[++index]` in the `push` method and the `array[index--]` in the `pop` method, with the word "equivalent" written in red between them.
- An arrow points from the `array[++index]` to the handwritten code `int i = index;` and `index = i + 1;`.
- A red bracket underlines the `array[index]` in the `peek` method, with the text "could read here!" written in red below it.

How Could This Be a Data Race? (1 of 2)

- ❖ It looks like `isEmpty` and `peek` can “get away with this” since `push` and `pop` adjust the state “in one tiny step”
- ❖ But this is an unsafe assumption about implementation details!
 - What looks like “tiny steps” in code may actually be multiple steps in the implementation:
 - `array[++index] = val` probably takes at least two steps
 - Compiler optimizations may modify “simple code” in unanticipated ways

How Could This Be a Data Race? (2 of 2)

- ❖ Since `push` and `pop` (ie, methods which *write*) probably require ≥ 2 steps, an unsynchronized *read* (eg, `isEmpty` and `peek`) will create a *data race*
 - See Grossman notes for more details

- ❖ **Moral:** Do not introduce a *data race*, even if every interleaving you can think of is correct

Summary

- ❖ Java locks are re-entrant
 - Use `finally` blocks or `synchronized` to ensure locks are released
- ❖ **“Race condition”** refers to different things, but both are the result of a lack of synchronization:
 - **Data races**: Simultaneous read/write or write/write of the same memory location
 - Always an error
 - Original `peek` example had no data races, but we introduced one later
 - **Bad interleavings**: Exposing intermediate state to other threads
 - Not all interleavings are “bad”
 - Original `peek` had several bad interleavings