



CSE 332: Data Abstractions

Lecture 21: Programming with Locks and Critical Sections

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Outline

Done:

- The semantics of locks
- Locks in Java
- Using locks for mutual exclusion: bank-account example

This lecture:

- More bad interleavings (learn to spot these!)
- Guidelines/idioms for shared-memory and using locks correctly
- Coarse-grained vs. fine-grained

Next lecture:

- Readers/writer locks
- Deadlock
- Condition variables
- Data races and memory-consistency models

Race Conditions

A **race condition** occurs when the computation result depends on scheduling (how threads are interleaved)

- If T1 and T2 happened to get scheduled in a certain way, things go wrong
- We, as programmers, cannot control scheduling of threads;
- Thus we need to write programs that work ***independent of scheduling***

Race conditions are bugs that exist only due to concurrency

- No interleaved scheduling problems with only 1 thread!

Typically, problem is that some *intermediate state* can be seen by another thread; screws up other thread

- Consider a ‘partial’ insert in a linked list; say, a new node has been added to the end, but ‘back’ and ‘count’ haven’t been updated

Race Conditions:

Data Races vs. Bad Interleavings

We will make a big distinction between *data races* and *bad interleavings*, both kinds of race-condition bugs

- Confusion often results from not distinguishing these or using the ambiguous “race condition” to mean only one

Data Races (briefly)

- A **data race** is a specific type of **race condition** that can happen in 2 ways:
 - Two different threads **potentially** write a variable at the same time
 - One thread **potentially** writes a variable while another reads the variable
- Not a race: simultaneous reads provide no errors
- ‘Potentially’ is important
 - We claim the code itself has a data race independent of any particular actual execution
- Data races are bad, but we can still have a race condition, and bad behavior, when no data races are present...through **bad interleavings** (our focus for this lecture).

Stack Example (pseudocode)

```
class Stack<E> {
    private E[] array = (E[])new Object[SIZE];
    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--];
    }
}
```

Example of a Race Condition, but not a Data Race

```
class Stack<E> {
    ... // state used by isEmpty, push, pop
    synchronized boolean isEmpty() { ... }
    synchronized void push(E val) { ... }
    synchronized E pop() {
        if(isEmpty())
            throw new StackEmptyException();
        ...
    }
    E peek() { // this is wrong
        E ans = pop();
        push(ans);
        return ans;
    }
}
```

peek, sequentially speaking

- In a sequential world, this code is of questionable *style*, but unquestionably *correct*
- The “algorithm” is the only way to write a **peek** helper method if all you had was this interface:

```
interface Stack<E> {
    boolean isEmpty();
    void push(E val);
    E pop();
}

class C {
    static <E> E myPeek(Stack<E> s) { ??? }
}
```

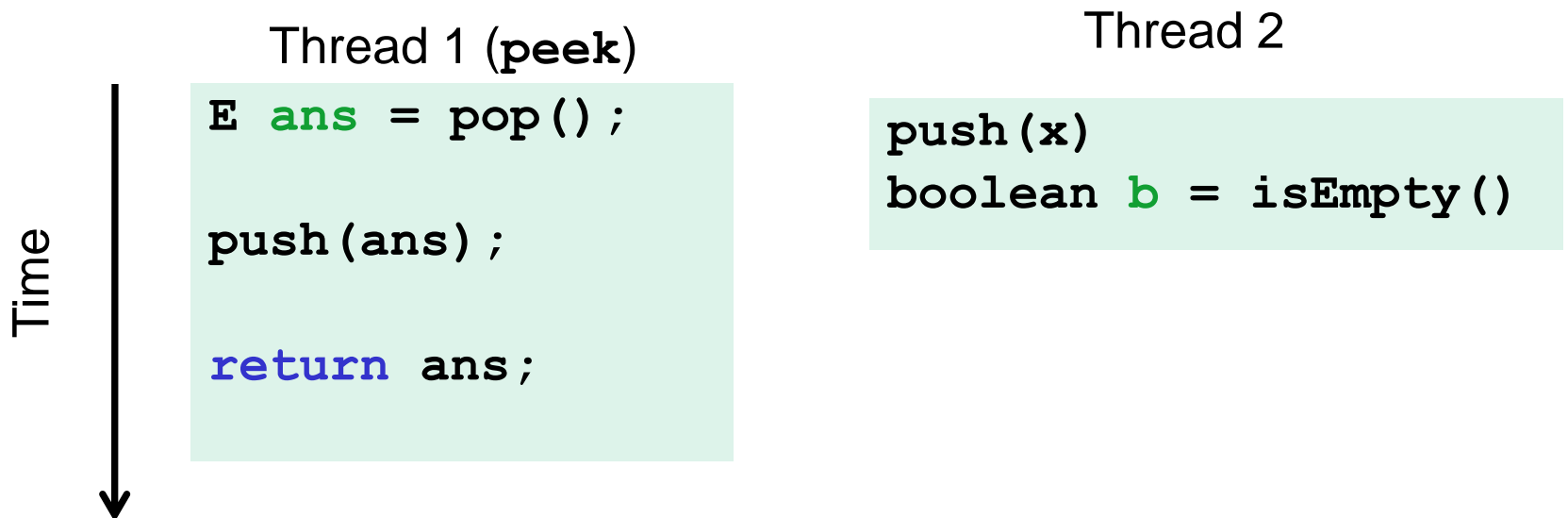

Problems with `peek`

```
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 after it executes as before
- But the way it is implemented creates an inconsistent *intermediate state*
 - Even though calls to `push` and `pop` are synchronized so there are no *data races* on the underlying array/list/whatever
 - Can’t access ‘top’ simultaneously
 - There is still a *race condition* though
- This intermediate state should not be exposed
 - Leads to several *bad interleavings*

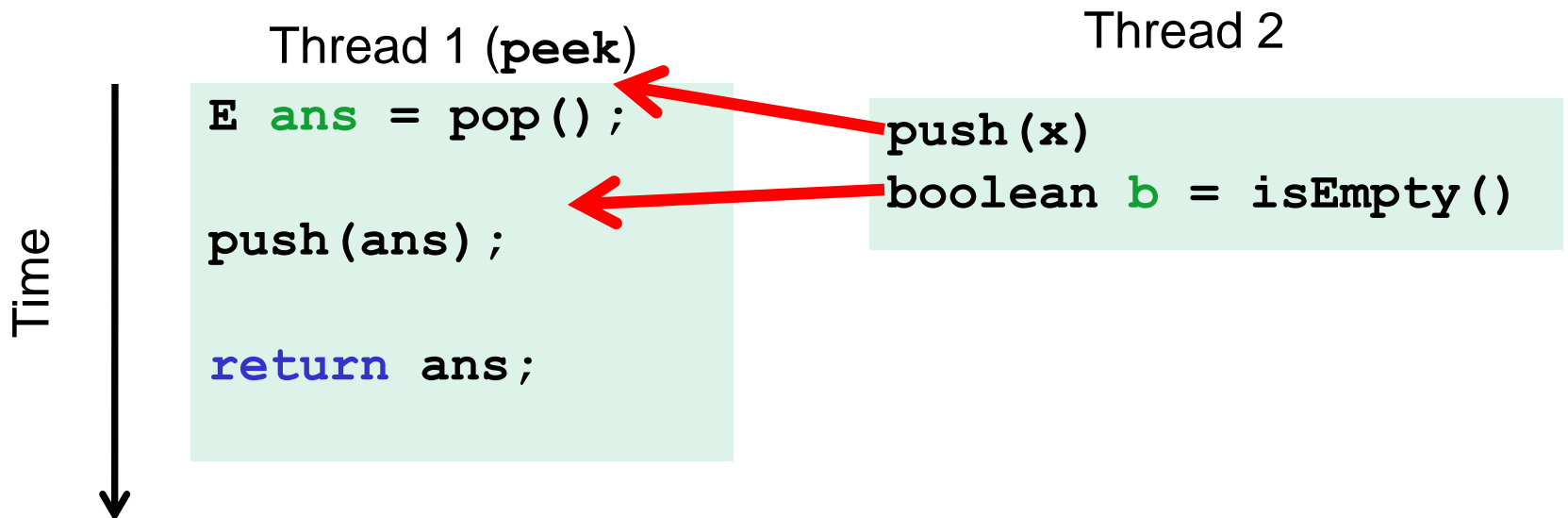
Example 1: peek and isEmpty

- **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?



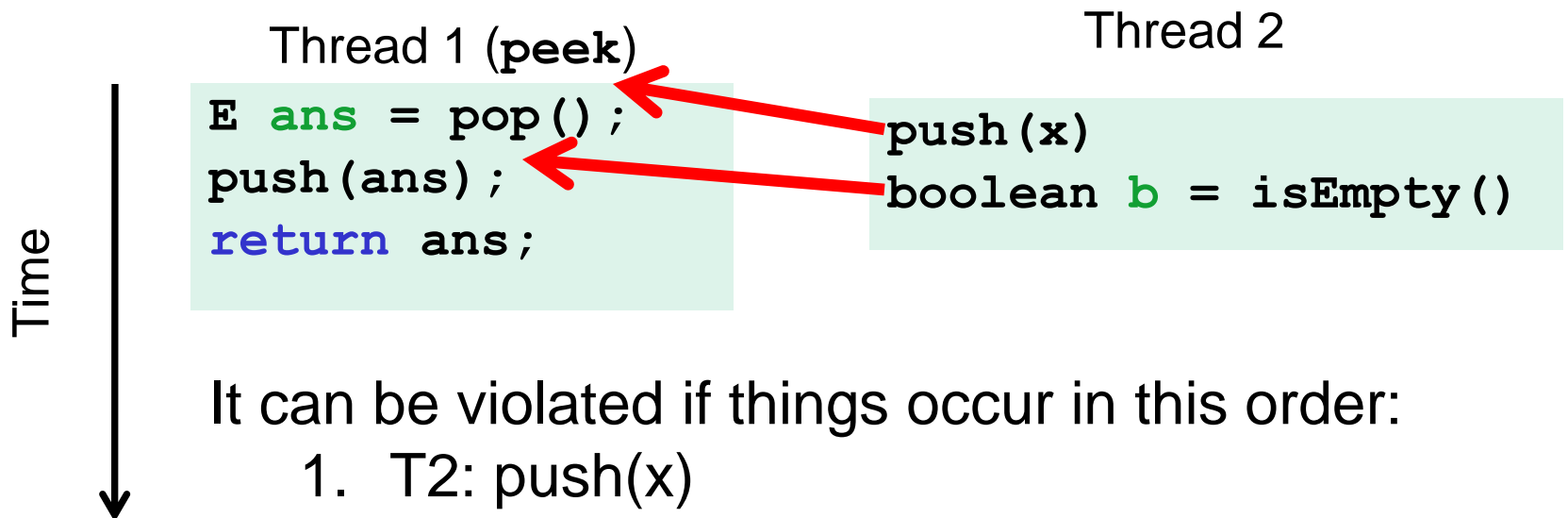
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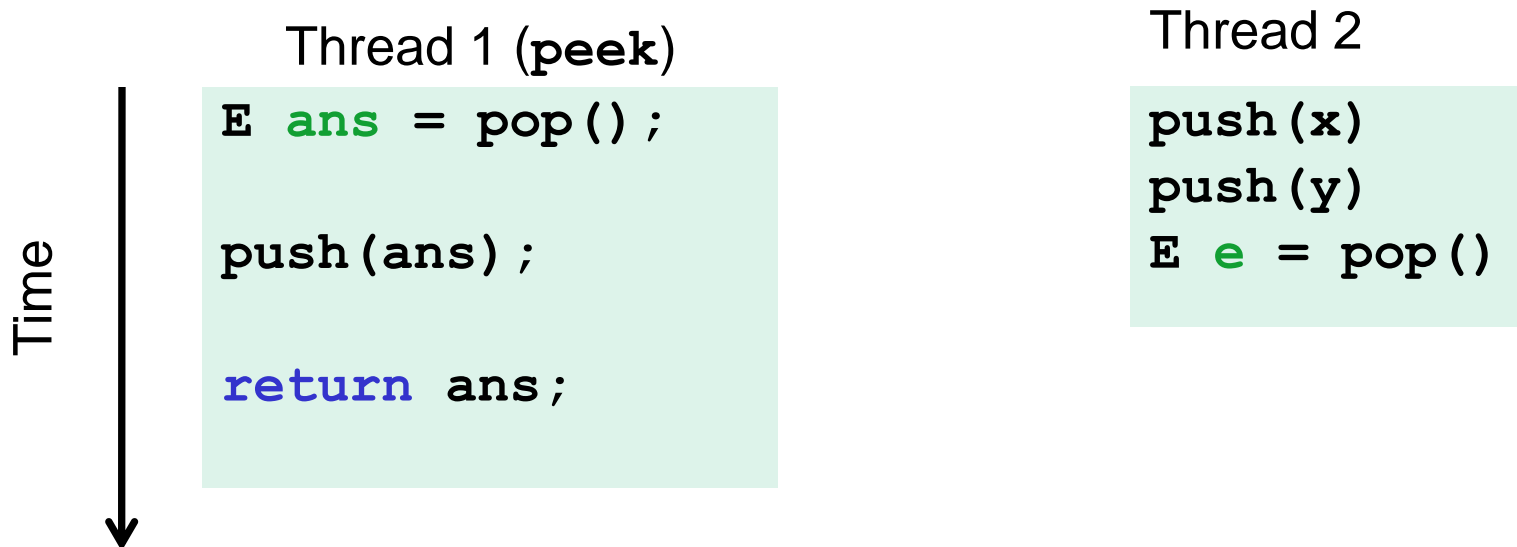


It can be violated if things occur in this order:

1. T2: push(x)
2. T1: pop()
3. T2: boolean b = isEmpty()

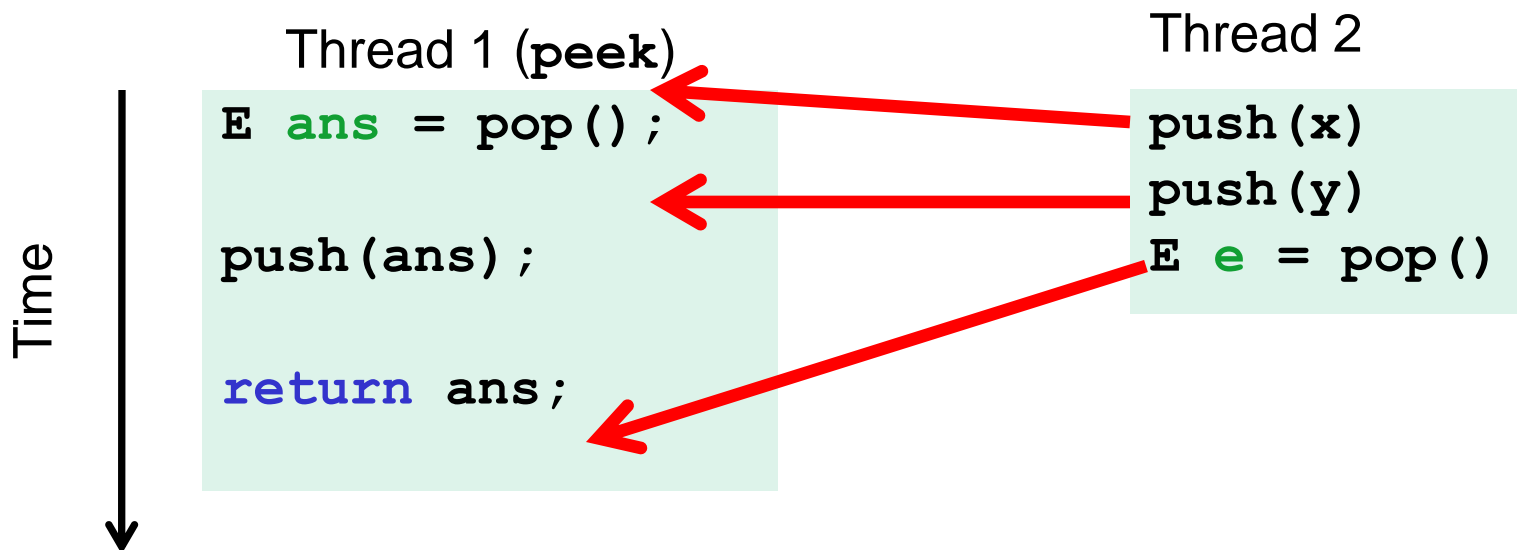
Example 2: peek and push

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



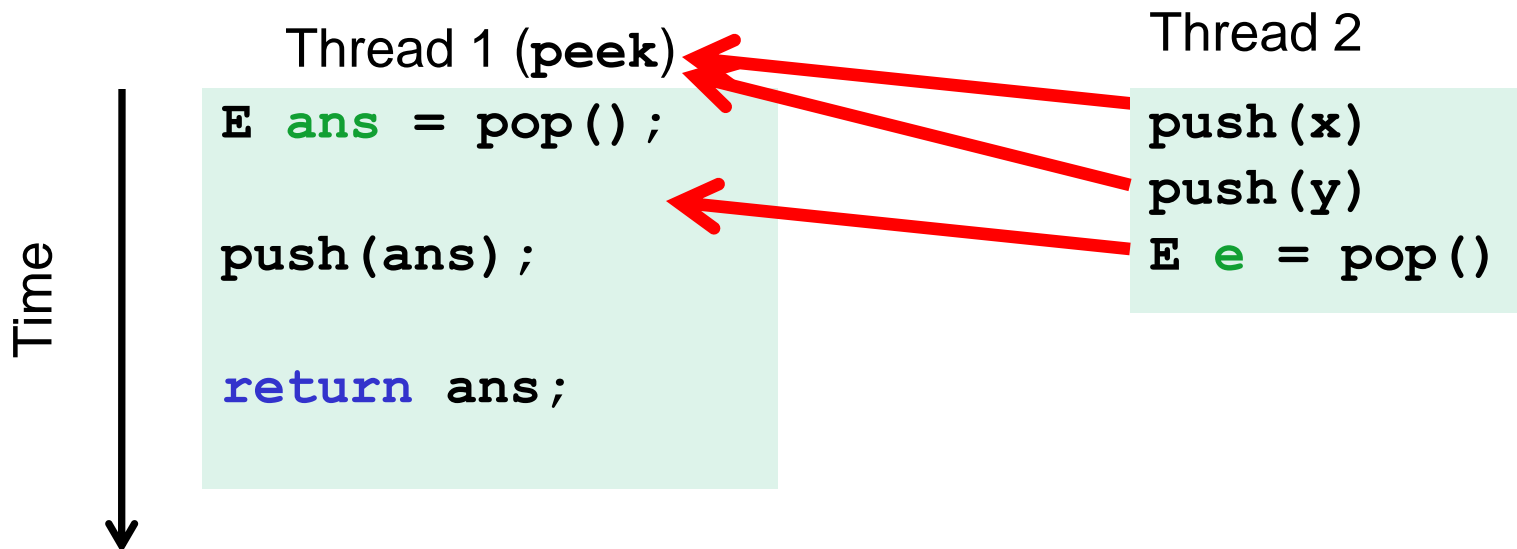
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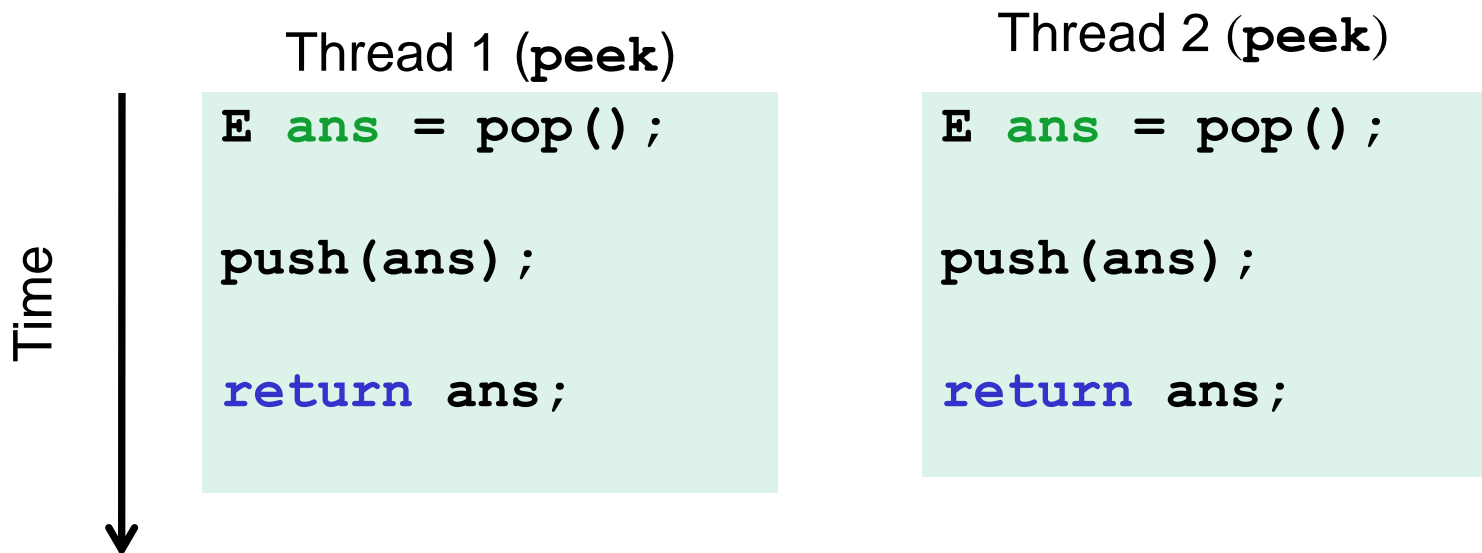
Example 3: peek and pop

- **Property we want:** Values are returned from `pop` in LIFO order
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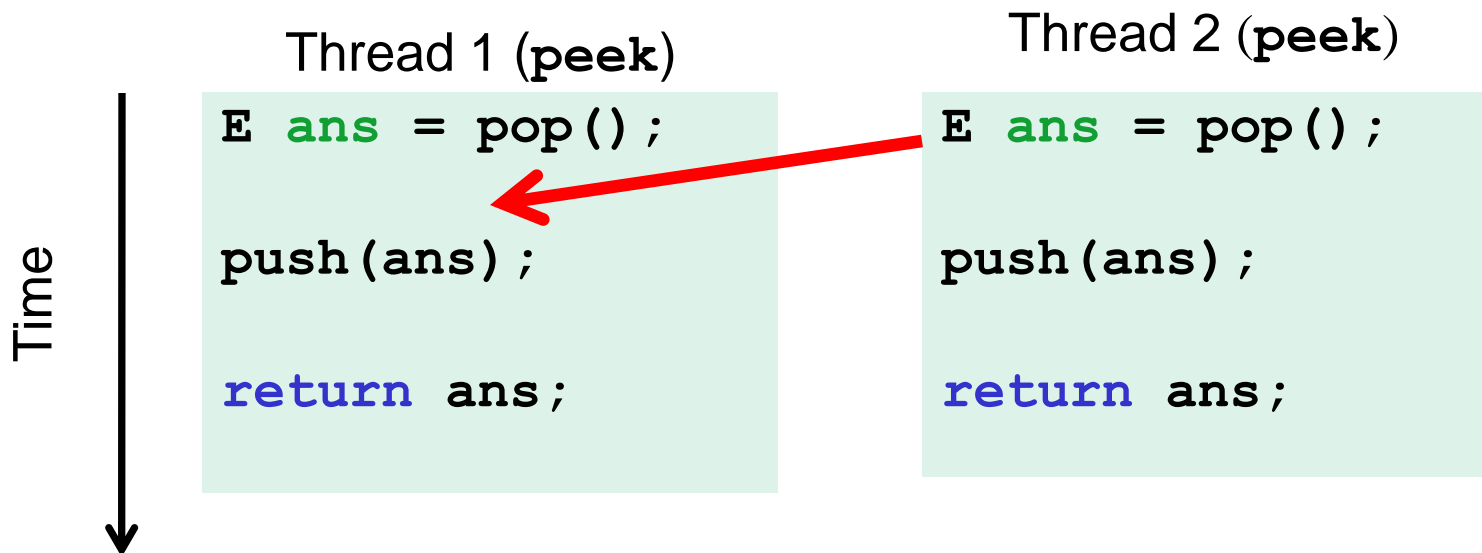
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- **Property we want:** `peek` doesn't throw an exception unless stack is empty
- With `peek` as written, property can be violated – how?



Example 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

- In short, **peek** needs synchronization to disallow interleavings
 - The key is to make a *larger critical section*
 - That intermediate state of `peek` needs to be protected
 - Use re-entrant locks; will allow calls to **push** and **pop**
 - Code on right is a `peek` external to the `Stack` class

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

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

The wrong “fix”

- **Focus so far:** problems from `peek` doing writes that lead to an incorrect intermediate state
- **Tempting but wrong:** If an implementation of `peek` (or `isEmpty`) does not write anything, then maybe we can skip the synchronization?
- Does **not** work due to *data races* with `push` and `pop...`

Example, (pseudocode not complete)

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

Why wrong?

- It *looks like* `isEmpty` and `peek` can “get away with this” since `push` and `pop` adjust the state “in one tiny step”
- But this code is still *wrong* and depends on language-implementation details you cannot assume
 - Even “tiny steps” may require multiple steps in the implementation: `array[++index] = val` probably takes at least two steps
 - Code has a **data race**, allowing very strange behavior
 - Compiler optimizations may break it in ways you had not anticipated
 - We’ll talk about this more in the future
- Moral: Do not introduce a data race, even if every interleaving you can think of is correct

The distinction

The (poor) term “race condition” can refer to two *different* things resulting from lack of synchronization:

1. **Data races:** Simultaneous read/write or write/write of the same memory location
 - (for mortals) **always an error**, due to compiler & HW (next lecture)
 - Original **peek** example has no data races
2. **Bad interleavings:** Despite lack of data races, exposing bad intermediate state
 - “Bad” depends on your specification
 - Original **peek** had several

Getting it right

Avoiding race conditions on shared resources is difficult

- What ‘seems fine’ in a sequential world can get you into trouble when multiple threads are involved
- Decades of bugs have led to some *conventional wisdom*: general techniques that are known to work

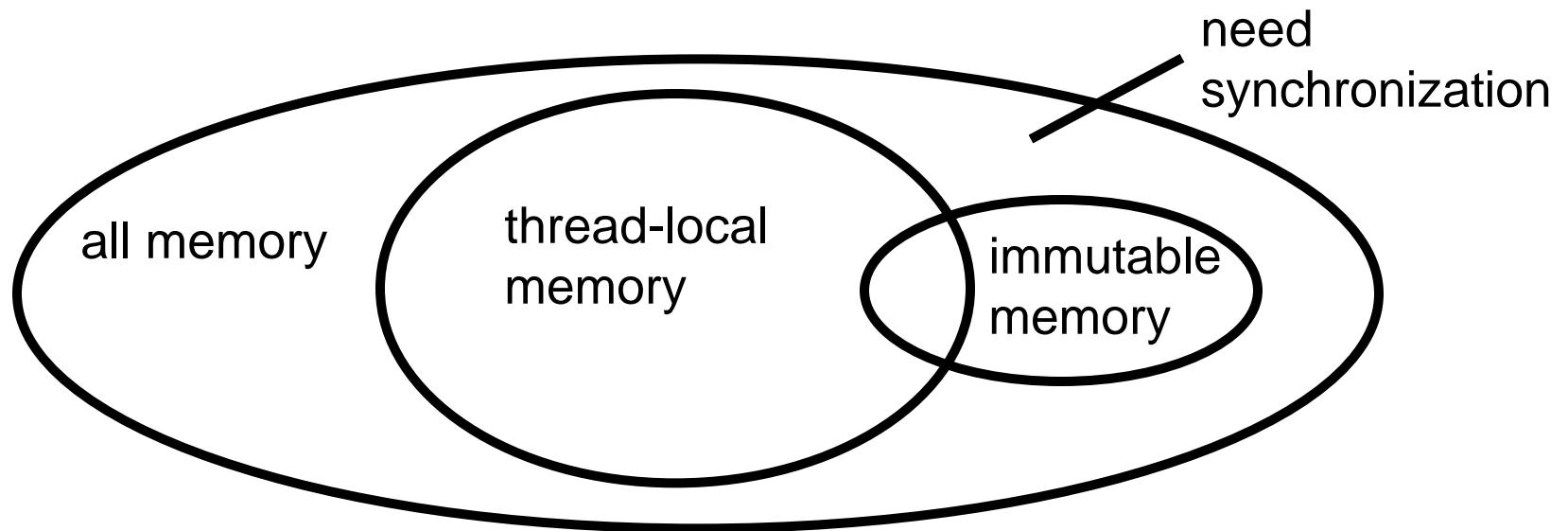
Rest of lecture distills key ideas and trade-offs

- Parts paraphrased from “Java Concurrency in Practice”
 - Chapter 2 (rest of book more advanced)
- But none of this is specific to Java or a particular book!
- May be hard to appreciate in beginning, but come back to these guidelines over the years – don’t try to be fancy!

3 choices

For every **memory location** (e.g., object field) in your program, you must obey at least one of the following:

1. **Thread-local**: Do not use the location in > 1 thread
2. **Immutable**: Do not write to the memory location
3. **Shared-and-mutable**: Use synchronization to control access to the location



Thread-local

Whenever possible, do not share resources

- Easier to have each thread have its own **thread-local copy** of a resource than to have one with shared updates
- This is correct only if threads do not need to communicate through the resource
 - That is, multiple copies are a correct approach
 - Example: **Random** objects
- Note: Because each call-stack is thread-local, never need to synchronize on local variables

In typical concurrent programs, the vast majority of objects should be thread-local: shared-memory should be rare – minimize it

Immutable

Whenever possible, do not update objects

- Make new objects instead!
- One of the key tenets of *functional programming* (see CSE 341)
 - Generally helpful to avoid *side-effects*
 - Much more helpful in a concurrent setting
- If a location is only read, never written, then no synchronization is necessary!
 - Simultaneous reads are *not* races and *not* a problem

In practice, programmers usually over-use mutation – minimize it

The rest: Keep it synchronized

After minimizing the amount of memory that is (1) thread-shared and (2) mutable, we need guidelines for how to use locks to keep other data consistent

Guideline #0: No data races

- *Never allow two threads to read/write or write/write the same location at the same time* (use locks!)
 - Even if it ‘seems safe’

Necessary:

- a Java or C program with a data race is almost always wrong
- Even if our reasoning tells us otherwise; ex: compiler optimizations

But Not sufficient: Our **peek** example had no data races, and it’s still wrong...

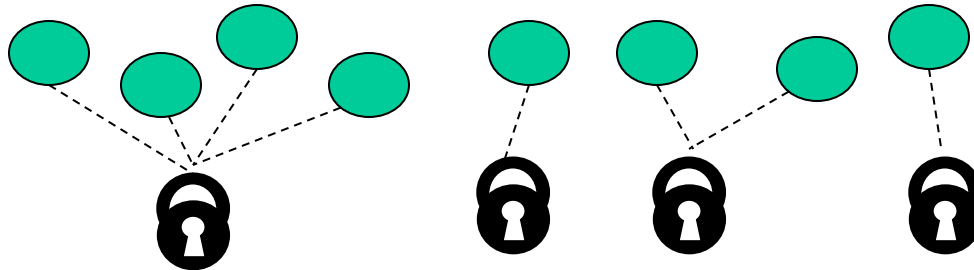
Consistent Locking

Guideline #1: Use consistent locking

- *For each location needing synchronization, have a lock that is always held when reading or writing the location*
- We say the lock **guards** the location
- The same lock can (and often should) guard multiple locations (ex. multiple fields in a class)
- Clearly document the guard for each location
- In Java, often the guard is the object containing the location
 - **this** inside the object's methods
 - But also often guard a larger structure with one lock to ensure mutual exclusion on the structure

Consistent Locking (continued)

- The mapping from locations to guarding locks is *conceptual*
 - Must be enforced by you as the programmer
- It partitions the **shared-and-mutable** locations into “which lock”



Consistent locking is:

- *Not sufficient*: It prevents all data races but still allows bad interleavings
 - Our **peek** example used consistent locking, but still had exposed intermediate states (and allowed potential bad interleavings)
- *Not necessary*: Can change the locking protocol dynamically...

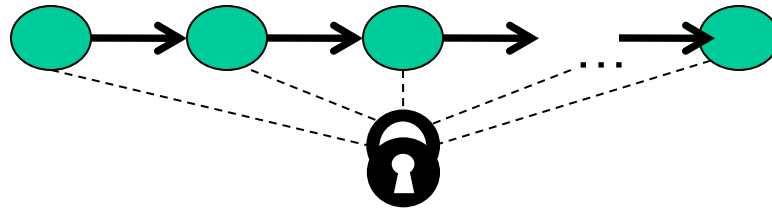
Beyond consistent locking

- Consistent locking is an excellent guideline
 - A “default assumption” about program design
 - You will save yourself many a headache using this guideline
- But it isn’t required for correctness: Can have different program phases use different invariants
 - Provided all threads coordinate moving to the next phase
- Example from Project 3, Version 5:
 - A shared grid being updated, so use a lock for each entry
 - But after the grid is filled out, all threads except 1 terminate
 - So synchronization no longer necessary (thread local)
 - And later the grid becomes immutable
 - So synchronization is doubly unnecessary

Lock granularity

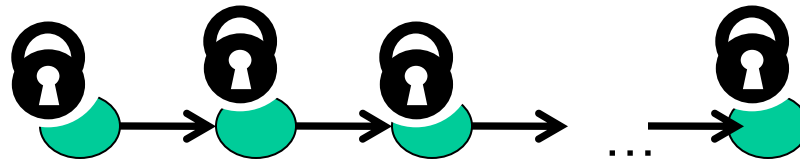
Coarse-grained: Fewer locks, i.e., more objects per lock

- Example: One lock for entire data structure (e.g., array)
- Example: One lock for all bank accounts



Fine-grained: More locks, i.e., fewer objects per lock

- Example: One lock per data element (e.g., array index)
- Example: One lock per bank account



“Coarse-grained vs. fine-grained” is really a continuum

Trade-offs

Coarse-grained advantages:

- Simpler to implement
- 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 advantages:

- More simultaneous access (performance when coarse-grained would lead to unnecessary blocking)
- Can make multi-node operations more difficult: say, rotations in an AVL tree

Guideline #2: *Start with coarse-grained (simpler) and move to fine-grained (performance) only if contention on the coarser locks becomes an issue.*

Example: Separate Chaining Hashtable

- Coarse-grained: One lock for entire hashtable
- Fine-grained: One lock for each bucket

Which supports more concurrency for **insert** and **lookup**?

Which makes implementing **resize** easier?

- How would you do it?

If a hashtable has a **numElements** field, maintaining it will destroy the benefits of using separate locks for each bucket, why?

Example: Separate Chaining Hashtable

- Coarse-grained: One lock for entire hashtable
- Fine-grained: One lock for each bucket

Which supports more concurrency for **insert** and **lookup**?

Fine-grained; allows simultaneous access to diff. buckets

Which makes implementing **resize** easier?

- How would you do it?
- Coarse-grained; just grab one lock and proceed

If a hashtable has a **numElements** field, maintaining it will destroy the benefits of using separate locks for each bucket, why?

Updating it each insert w/o a lock would be a data race

Critical-section granularity

A second, orthogonal granularity issue is critical-section size

- How much work to do while holding lock(s)?

If critical sections run for too long?

–

If critical sections are too short?

–

Critical-section granularity

A second, orthogonal granularity issue is critical-section size

- How much work to do while holding lock(s)?

If critical sections run for too long:

- Performance loss because other threads are blocked

If critical sections are too short:

- Bugs because you broke up something where other threads should not be able to see intermediate state

Guideline #3: *Don't do expensive computations or I/O in critical sections, but also don't introduce race conditions; keep it as small as possible but still be correct*

Example 1: Critical-section granularity

Suppose we want to change the value for a key in a hashtable without removing it from the table

- Assume `lock` guards the whole table
- `expensive()` takes in the old value, and computes a new one, but takes a long time

```
synchronized(lock) {  
    v1 = table.lookup(k);  
    v2 = expensive(v1);  
    table.remove(k);  
    table.insert(k, v2);  
}
```

Example 1: Critical-section granularity

Suppose we want to change the value for a key in a hashtable without removing it from the table

- Assume `lock` guards the whole table
- `expensive()` takes in the old value, and computes a new one, but takes a long time

*Papa Bear's
critical section
was too long*

*(table locked
during
expensive call)*

```
synchronized(lock) {  
    v1 = table.lookup(k);  
    v2 = expensive(v1);  
    table.remove(k);  
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}
```

Example 2: Critical-section granularity

Suppose we want to change the value for a key in a hashtable without removing it from the table

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}  
v2 = expensive(v1);  
synchronized(lock) {  
    table.remove(k);  
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}
```

Example 2: Critical-section granularity

Suppose we want to change the value for a key in a hashtable without removing it from the table

- Assume `lock` guards the whole table

*Mama Bear's
critical section
was too short*

*(if another thread
updated the entry,
we will lose an
update)*

```
synchronized(lock) {  
    v1 = table.lookup(k);  
}  
v2 = expensive(v1);  
synchronized(lock) {  
    table.remove(k);  
    table.insert(k, v2);  
}
```


Example 3: Critical-section granularity

Suppose we want to change the value for a key in a hashtable without removing it from the table

- Assume `lock` guards the whole table

```
done = false;
while (!done) {
    synchronized(lock) {
        v1 = table.lookup(k);
    }
    v2 = expensive(v1);
    synchronized(lock) {
        if (table.lookup(k) == v1) {
            done = true; // I can exit the loop!
            table.remove(k);
            table.insert(k, v2);
        }
    }
}
```

Example 3: Critical-section granularity

Suppose we want to change the value for a key in a hashtable without removing it from the table

- Assume `lock` guards the whole table

*Baby Bear's
critical section
was just right*

*(if another update
occurred, try our
update again)*

```
done = false;
while (!done) {
    synchronized(lock) {
        v1 = table.lookup(k);
    }
    v2 = expensive(v1);
    synchronized(lock) {
        if (table.lookup(k) == v1) {
            done = true; // I can exit the loop!
            table.remove(k);
            table.insert(k, v2);
        }
    }
}
```

Atomicity

An operation is *atomic* if no other thread can see it partly executed

- Atomic as in “appears indivisible”
- Typically want ADT operations atomic, even to other threads running operations on the same ADT

Guideline #4: *Think in terms of what operations need to be atomic*

- Make critical sections just long enough to preserve atomicity
- *Then* design the locking protocol to implement the critical sections correctly

That is: Think about atomicity first and locks second

Don't roll your own

- In “real life”, it is unusual to have to write your own data structure from scratch
 - Implementations provided in standard libraries
 - Point of CSE332 is to understand the key trade-offs, abstractions, and analysis of such implementations
- Especially true for concurrent data structures
 - Far too difficult to provide fine-grained synchronization without race conditions
 - Standard **thread-safe** libraries like **ConcurrentHashMap** written by world experts

Guideline #5: *Use built-in libraries whenever they meet your needs*