

Lecture 22:

Race Conditions & Deadlock

CSE 332: Data Structures & Parallelism

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Announcements

- EX10 due today
- EX11 released
- Exam 2 information posted here: *7 days*
 - <https://courses.cs.washington.edu/courses/cse332/25su/exams/final.html>
 - **Note: it will be hard to accommodate makeups; only four days to grade**
 - If you can't make proposed makeup dates (e.g., sickness/emergency), some options:
 - Option 1: Exam 1 is worth 40% instead of 20% of overall grade
 - Option 2: Take the final exam in the next CSE 332 offering

Today

- Concurrency: Synchronization
 - Concurrent Programming
 - Mutual Exclusion (Mutex)
 - Locks
 - Re-entrant Locks
- Concurrency: Synchronization Issues
 - Race Conditions: Data Races & Bad Interleavings
 - Deadlocks

Race Conditions

"A **race condition** is a mistake in your program (i.e., a bug) such that whether the program behaves correctly or not depends on the order that the threads execute."

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

Race Conditions:

Data Races vs. Bad Interleavings

We will make a big distinction between:

data races and *bad interleavings*

Data Races

A **data race** is a specific type of **race condition** where there is the **possibility** for either:

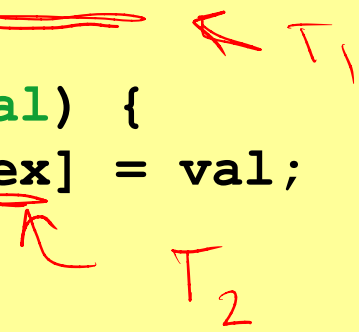
1. Two different threads to write a variable at the same time
 - Write-Write
2. One thread reads a variable while another thread writes the same variable at the same time
 - Read-Write

or memory location

→ arriving

Stack Example (pseudocode)

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



Stack Example (pseudocode)

```
class Stack<E> {  
    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--];  
    }  
}
```


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(); ①  
        push(ans); ②  
        return ans;  
    }  
}
```

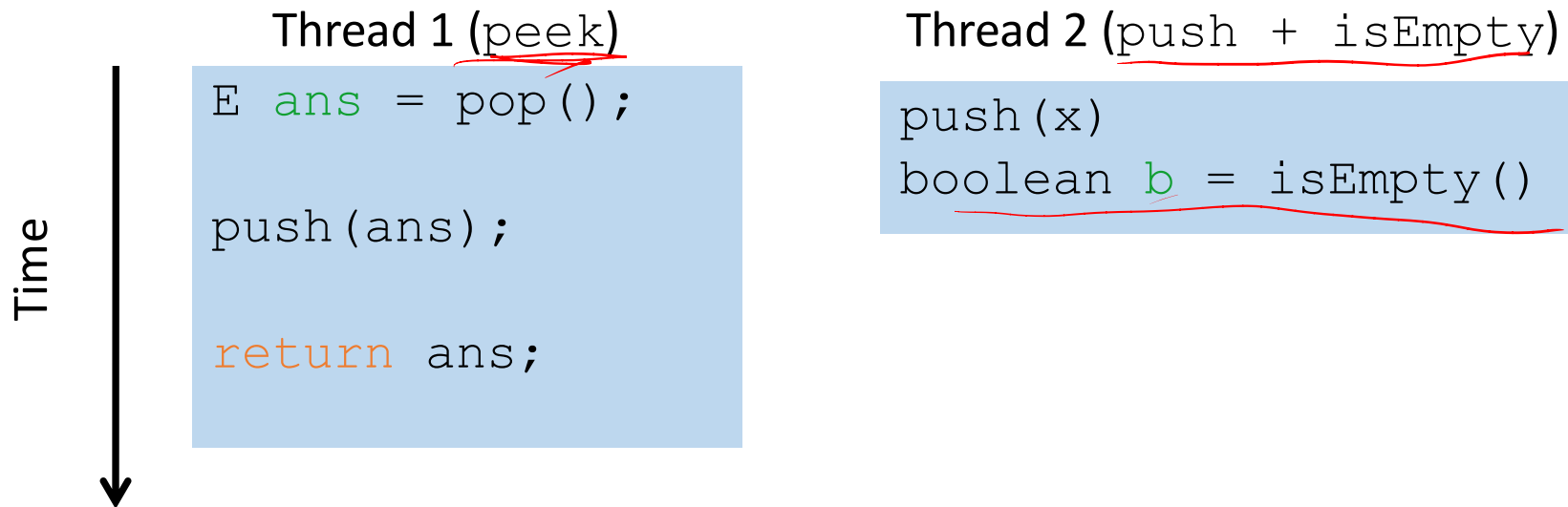
Problems with **peek**

```
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
 - Calls to push and pop are synchronized
 - So there are no data races on the underlying array/index
 - There is still a **race condition** though
- This intermediate state should not be exposed
 - Leads to several bad interleavings

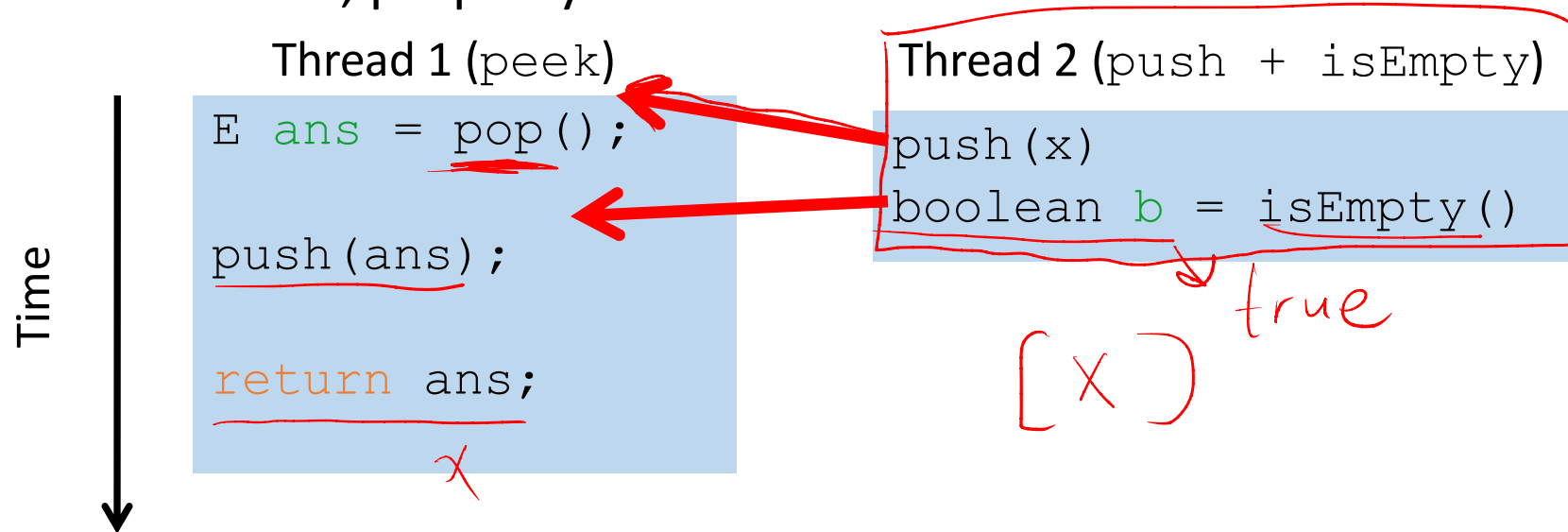
Example 1: peek and isEmpty

- **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?



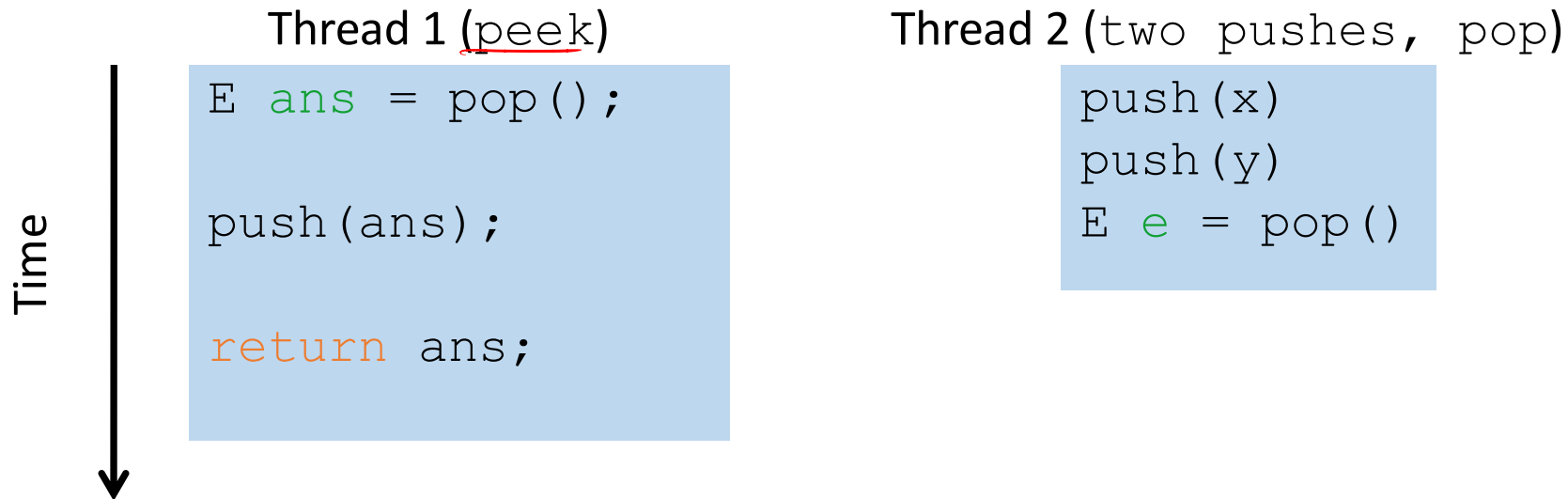
Example 1: peek and isEmpty

- **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?



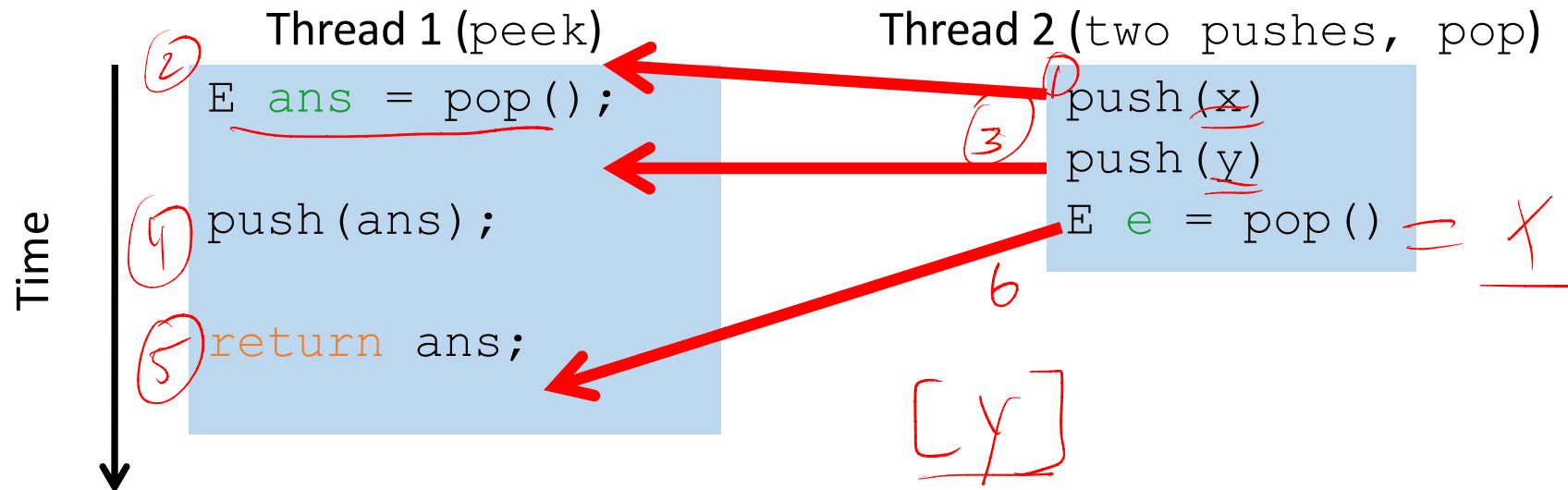
Example 2: peek and push

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



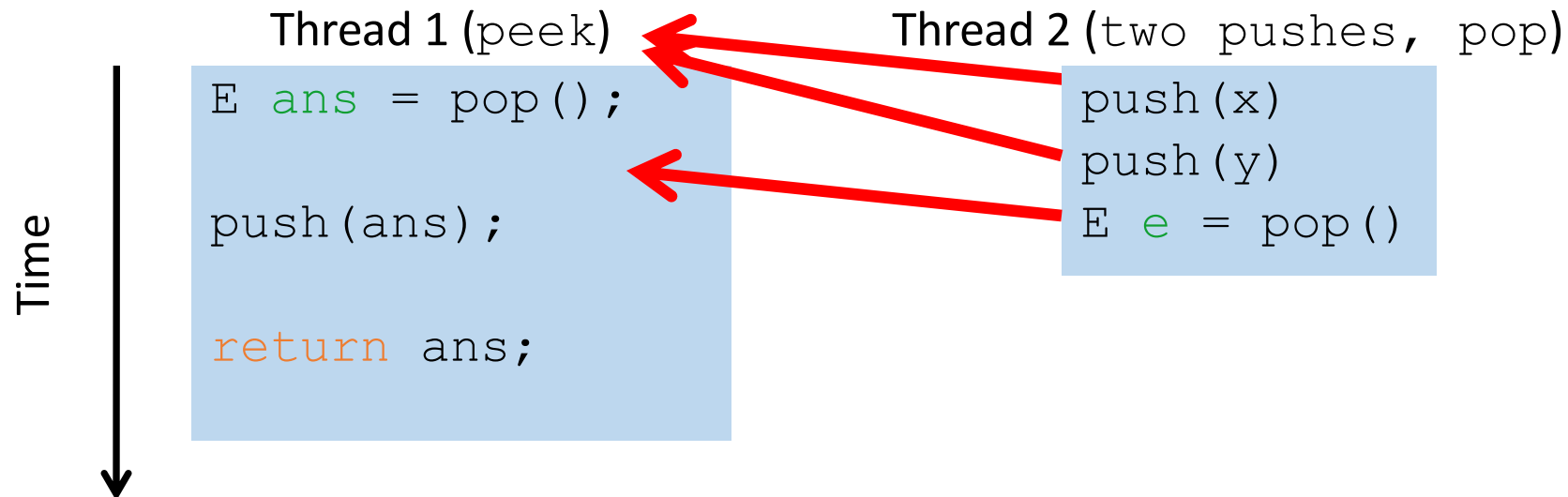
Example 2: peek and push

- **Property we want:** Values are returned from **pop** in LIFO order
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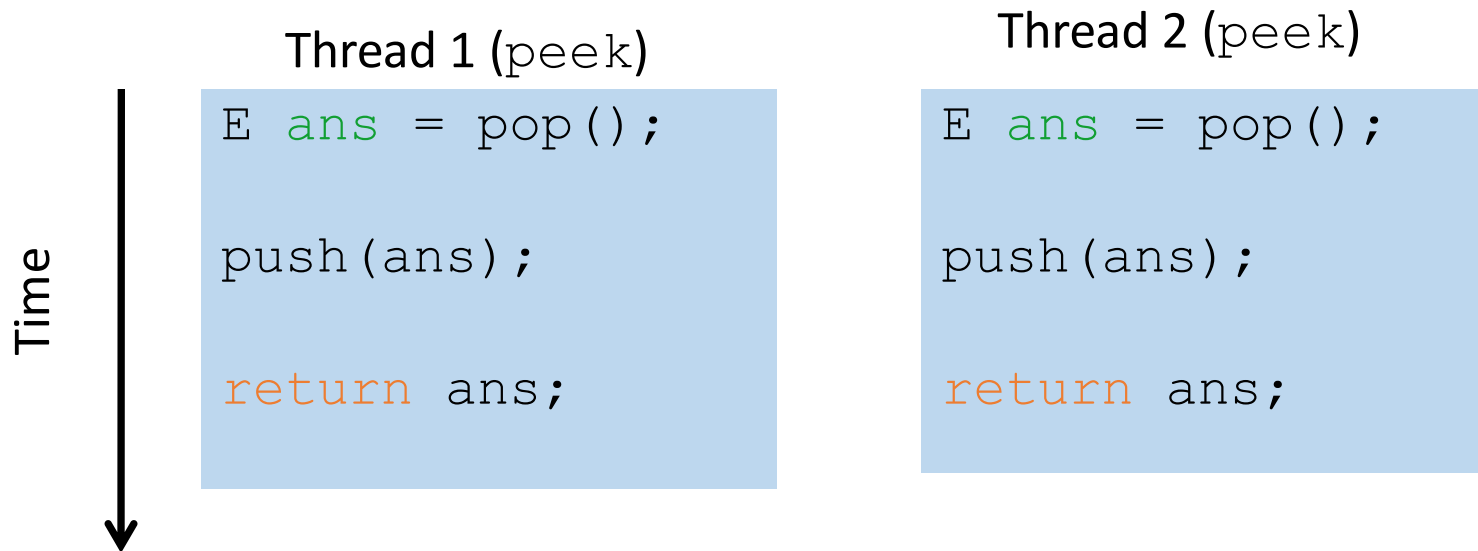
Example 2.5: peek and pop

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



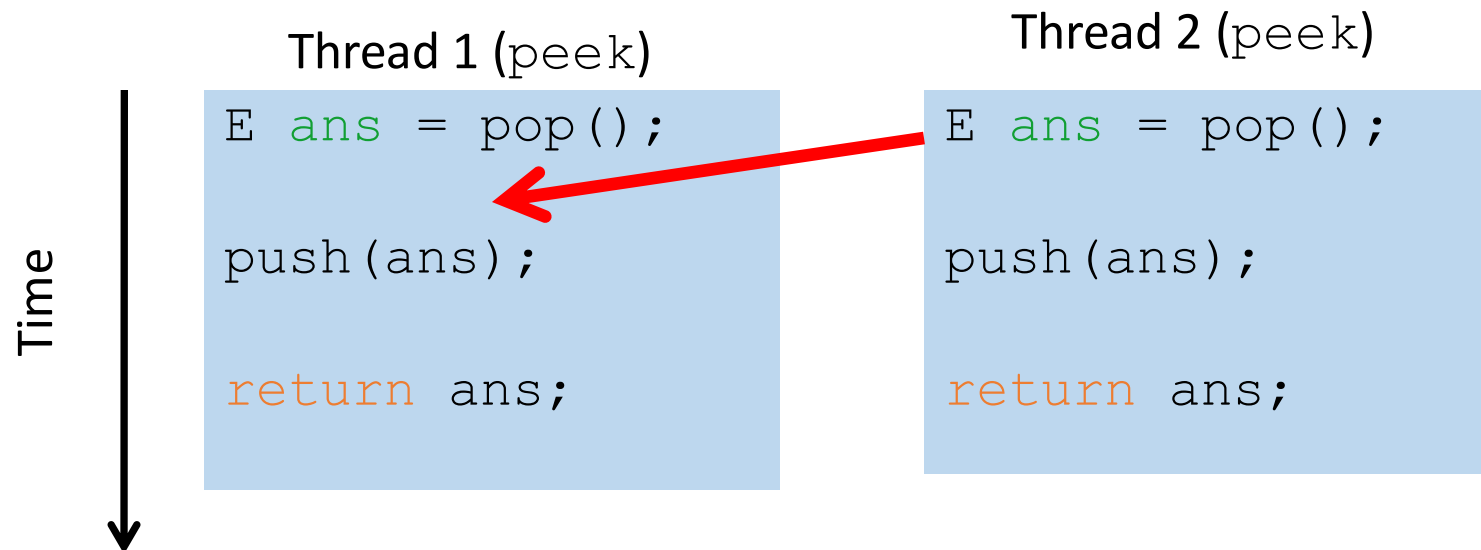
Example 4: peek and peek

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



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 example of 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;  
        }  
    }  
}
```

How you might have written peek

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

The wrong “fix”

- **Focus so far:** problems from (a weird) **peek** doing writes that lead to an incorrect intermediate state (bad interleavings)
- **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**...

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
 - See Grossman notes for more details
- Moral: Do not introduce a **data race**, even if every interleaving you can think of is correct

Recap: the distinction

The 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
2. **Bad interleavings**: Exposes bad intermediate state to other threads, leads to behavior **we** find incorrect
 - “Bad” depends on your specification

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

Next, we discuss this conventional wisdom!

- 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!

Conventional Wisdom

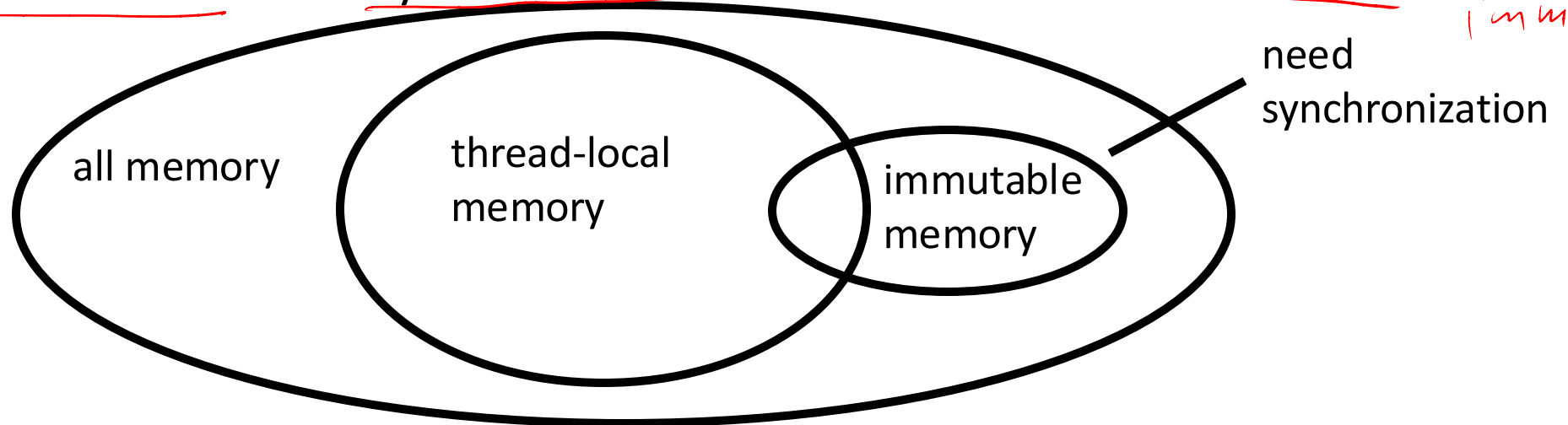
See Section 8 in Grossman Notes

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

have local variable as much as possible
have data types or objects that are immutable



1. 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*

2. 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

3. 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 by definition wrong

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

Consistent Locking

sync(this) {
 X
}

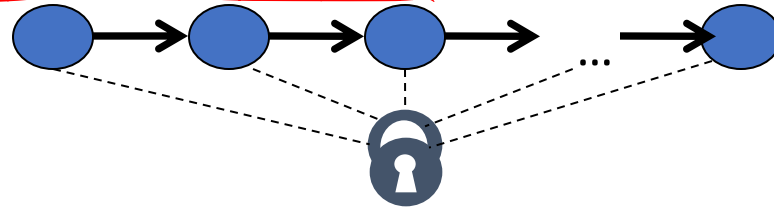
Guideline #1: Use consistent locking

- Every location needing synchronization has 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

Lock granularity

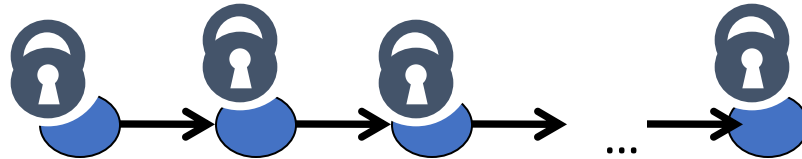
Coarse-grained: Fewer locks, i.e., more objects per lock

- 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

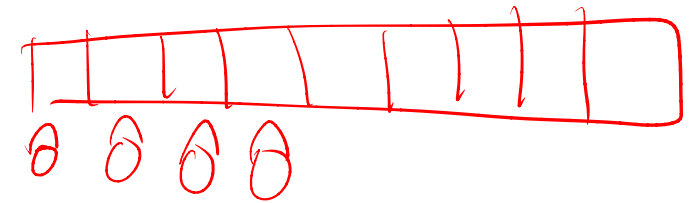


“Coarse-grained vs. fine-grained” is really a continuum

bob



Alice



0

0

0

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**?

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

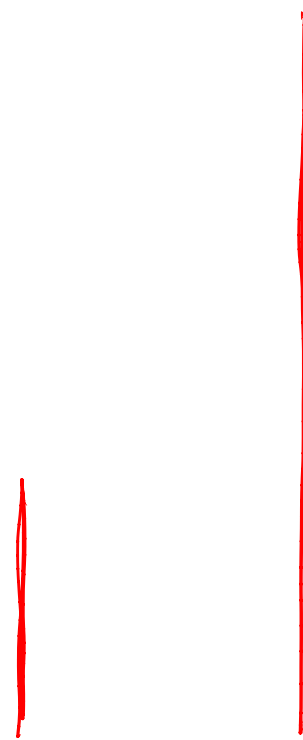
Critical-section granularity

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)?

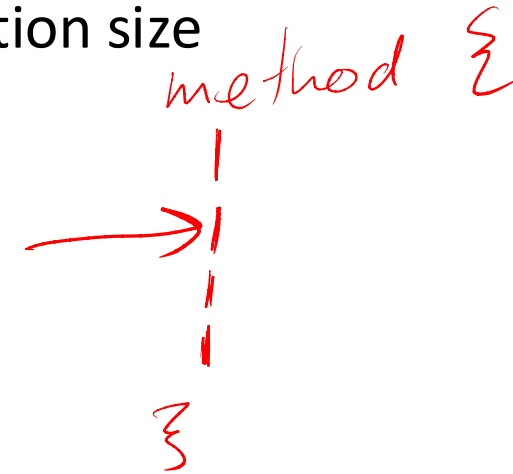
If critical sections run for **too long**:

- 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 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

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

Atomicity

push {

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

Deadlock

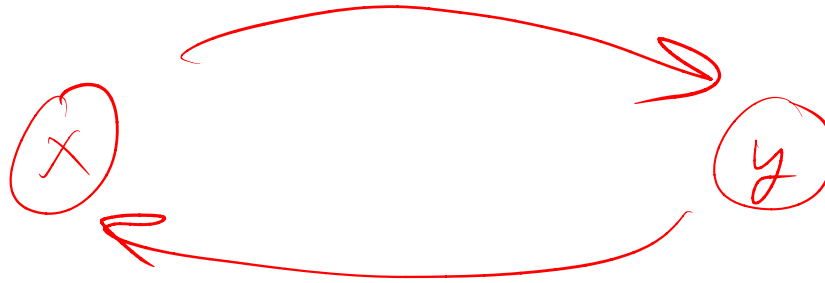
Motivating Deadlock Issues

Consider a method to transfer money between bank accounts

```
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);  
    }  
}
```

Potential problems?

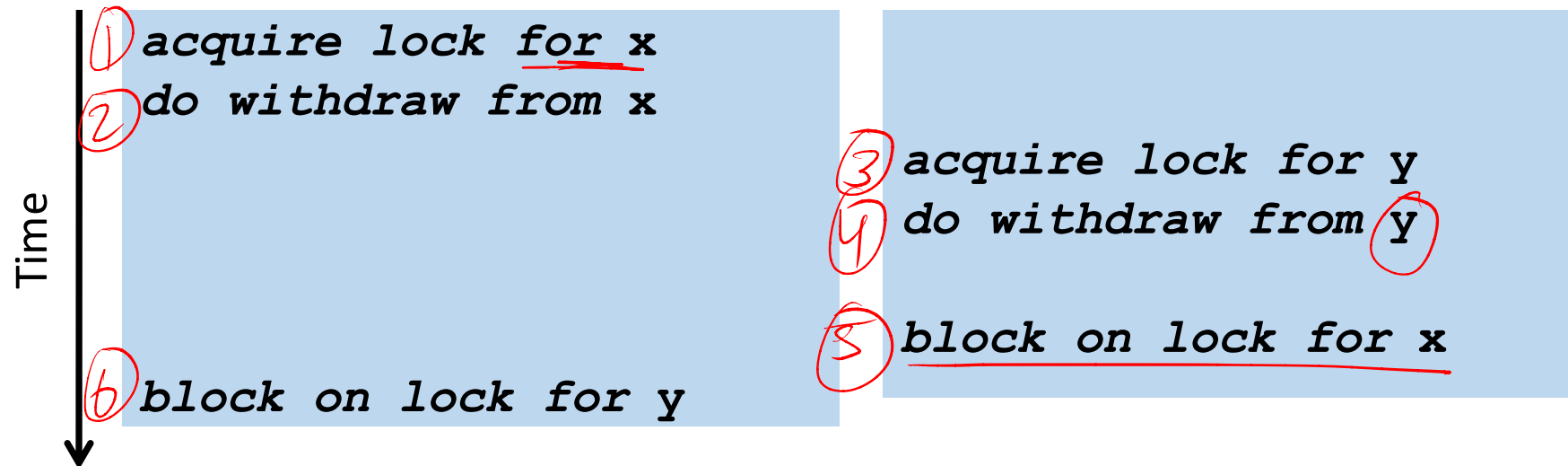
The Deadlock



Suppose **x** and **y** are static fields holding accounts

Thread 1: x.transferTo(1, y)

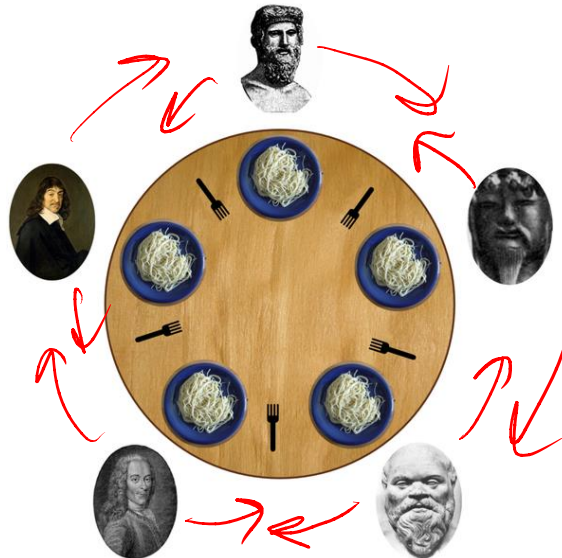
Thread 2: y.transferTo(1, x)



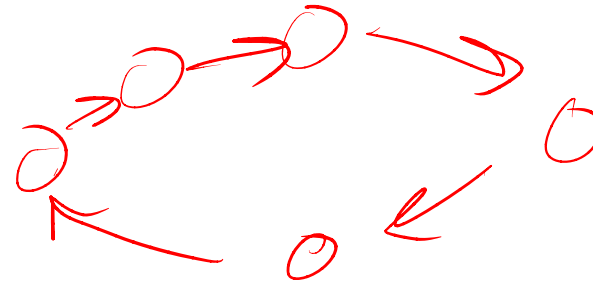
Thread 1 has lock on x

Another presentation: The Dining Philosophers

- 5 philosophers go out to dinner together at an Italian restaurant
- Sit at a round table; one fork per setting
- When the spaghetti comes, each philosopher proceeds to grab their right fork, then their left fork, then eats
- 'Locking' for each fork results in a ***deadlock***



Deadlock, in general



A deadlock occurs when we have a cycle of dependencies

ie: there are threads T_1, \dots, T_n such that:

- Thread T_i is waiting for a resource held by T_{i+1} and
- T_n is waiting for a resource held by T_1

Deadlock avoidance in programming amounts to techniques to ensure a cycle can never arise

Back to our example

Options for deadlock-proof transfer:

1. Make a smaller critical section: transferTo not synchronized
 - Exposes intermediate state after withdraw before deposit
 - May be okay here, but exposes wrong total amount in bank
2. Coarsen lock granularity: one lock for all accounts allowing transfers between them
 - Works, but sacrifices concurrent deposits/withdrawals
3. Give every bank-account a unique number and always acquire locks in the same order
 - *Entire program* should obey this order to avoid cycles
 - Code acquiring only one lock can ignore the order

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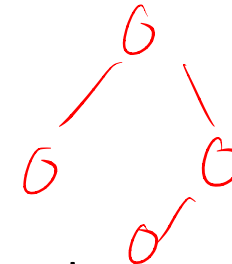
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Ordering locks

```
class BankAccount {
    ...
    private int acctNumber; // must be unique
    void transferTo(int amt, BankAccount a) {
        if(this.acctNumber < a.acctNumber)
            synchronized(this) {
                synchronized(a) {
                    this.withdraw(amt);
                    a.deposit(amt);
                }
            }
        else
            synchronized(a) {
                synchronized(this) {
                    this.withdraw(amt);
                    a.deposit(amt);
                }
            }
    }
}
```

Perspective

- Code like account-transfer are more sneaky examples of deadlock
- Easier case: different types of objects
 - Can document a fixed order among types
 - Example: "When moving an item from the hashtable to the work queue, never try to acquire the queue lock while holding the hashtable lock"
- Easier case: objects are in an acyclic structure
 - Can use the data structure to determine a fixed order
 - Example: "If holding a tree node's lock, do not acquire other tree nodes' locks unless they are children in the tree"



Concurrency summary

- Concurrent programming allows multiple threads to access shared resources (e.g. hash table, work queue)
- Introduces new kinds of bugs:
 - Race Conditions { Data races and Bad Interleavings }
 - Critical sections too small
 - Critical sections use wrong locks
 - Deadlocks
- Requires synchronization
 - Locks for mutual exclusion (common, various flavors)
 - Other Synchronization Primitives: (see Grossman notes)
 - Reader/Writer Locks
 - Condition variables for signaling others
- Guidelines for correct use help avoid common pitfalls

Any Questions?