Parallel Programming

Shared memory concurrency, locks and data races

Toward sharing resources (memory)

Have been studying parallel algorithms using fork-join

- Lower span via parallel tasks

Algorithms all had a simple *structure* to avoid race conditions

- Each thread had memory “only it accessed”, e.g: array sub-range
- On **`fork`**, “loan” some memory to “forkee” and do not access that memory again until after **`join`** on the “forkee”

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)

Managing state

Main challenge for parallel programs

Approaches:

- immutability
  - data do not change
  - best option, should be used when possible
- isolated mutability
  - data can change, but only one thread/task can access them
- mutable/shared data
  - data can change / all tasks/threads can potentially access them

Key properties of good parallel software

1) Safe from bugs : eliminate concurrency bugs by design

2) Easy to understand : simple design patterns
↳ which thread interleavings are / are not possible

3) Ready for change : changes without re-writing
↳ programmer knows what the code depends on for its thread safety

Mutable/Shared data

- present in shared memory architectures
- **however:** concurrent accesses may lead to inconsistencies
- **solution:** protect state by allowing only **one** task/thread to access it at a time

Dealing with mutable/shared state

State needs to be protected (in general)

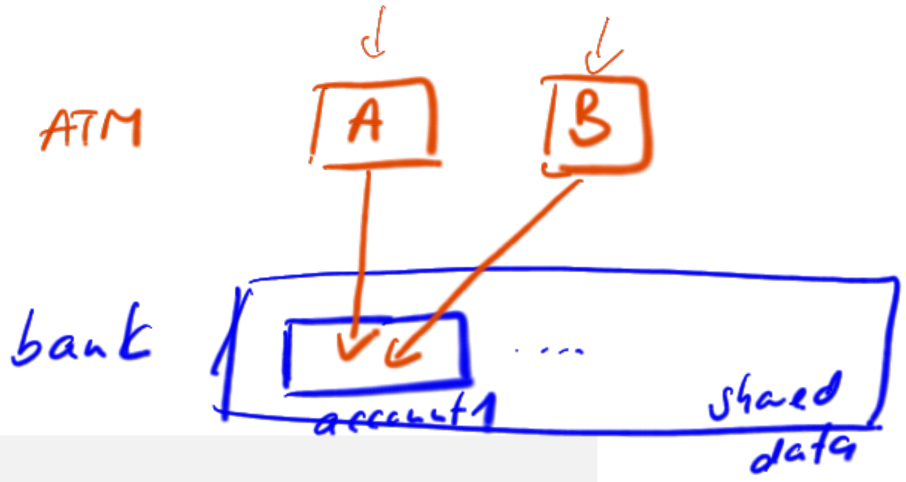
- exclusive access
- intermediate inconsistent states should not be observed

Methods:

- locks: mechanism to ensure exclusive access/atomicity
  - ensuring good performance / correctness with locks can be hard (especially for "programming in the large")

- Transactional memory: programmer describes a set of actions that need to be atomic
  - easier for the programmer, but getting good performance might be challenging

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.
}
```

A bad interleaving

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

- Assume initial **`balance == 150`**

Time

Thread 1

```
int b = getBalance();   150




if(amount > b)   100 > 150?
  throw new …;
setBalance(b – amount);   50
```

Thread 2

```
int b = getBalance();   150
if(amount > b)   100 > 150?
  throw new …;
setBalance(b – amount);   50
```

"Lost withdraw"!

⇒ balance = 50

Interleaving (recap)

If second call starts before first ends, we say the calls interleave

- Could happen even with one processor since a thread can be pre-empted at any point for time-slicing

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…

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);
}
```

1) getBalance
2) subtraction
3) setBalance

multiple steps
compiler

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?

Mutual exclusion

Sane 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: an account) means another thread must wait

- a.k.a. critical sections, which technically have other requirements

Programmer 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!

Wrong!

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

- 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
}
```

Just moved the problem!

Thread 1

```
while(busy) { }

busy = true;

int b = getBalance();




if(amount > b)
   throw new …;
setBalance(b - amount);
```

Thread 2

```

while(busy) { }

busy = true;

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

Time

"Lost withdraw

What we need

- Many ways out of this conundrum, but we need help from the language

- A basic solution: Locks
  - Not Java yet, though Java's approach is similar and slightly more convenient

- Basic synchronization primitive 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!]
  - `release`: makes this lock *"not held"*
    - If >= 1 threads are blocked on it, exactly 1 will acquire it

Why that works

- A primitive with atomic operations **`new`**, **`acquire`**, **`release`**

- The lock implementation ensures that given simultaneous acquires and/or releases, a correct thing will happen
  - Example: 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
  - Here, we take this as a primitive and use it

Topics Today

- Critical Sections, Mutual Exclusion, Lock Objects
- Java's **synchronized** (recap)
- Races: Data Races and Bad Interleavings
- Guidelines for Concurrent Programming

Critical Sections and Mutual Exclusion

Critical Section

Piece of code that may be executed by at most one process (thread) at a time

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

Mutual exclusion

Algorithm to implement a critical section

```
acquire_mutex();   // entry algorithm
...                // critical section
release_mutex();   // exit algorithm
```

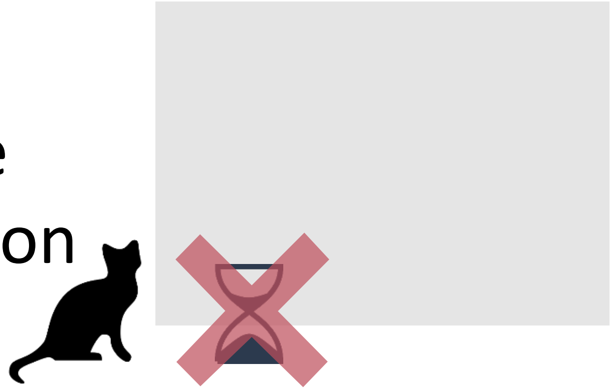
Required Properties of Mutual Exclusion

Safety Property

- At most one process executes the critical section code

Liveness

- *Minimally*: acquire_mutex must terminate in finite time when no process executes in the critical section



```
public synchronized void update {
    ... // critical section
}
```

=

```
public void update {
    synchronize(this) {
        ... // critical section
    }
}
```

```
private object lock = new object();

public void update {
    ...
    synchronized(lock) {
        ... // critical section
    }
}
```

external locks

java.util.concurrent.locks

```
private Lock mylock = new Lock();

public void update() {
    ...
    mylock.lock();
    ⋮ // critical section
    mylock.unlock();
}
```

not correct yet → try .. finally

```
public void update() {
    mylock.lock();
    try {
        // critical section
    }
    finally {
        mylock.unlock();
    }
}
```

Lock Object

Shared object that satisfies the following interface

```
public interface Lock{
        public void lock();      // entering CS
        public void unlock();    // leaving CS
}
```

providing the following semantics

`new Lock`	make a new lock, initially *"not held"*
`acquire`	blocks (only) if this lock is already currently *"held"* Once *"not held"*, makes lock *"held"* [all at once!]
`release`	makes this lock *"not held"* If >= 1 threads are blocked on it, exactly 1 will acquire it

Why that works

The lock implementation ensures that given simultaneous acquires and/or releases, a correct thing will happen

- Example: Two acquires: one will “win” and one will block
- A lock thus implements a mutual exclusion algorithm.

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
- For the time being, we take this as a primitive and use it

Almost-correct pseudocode

```
class BankAccount {
   private int balance = 0;
   private Lock lk = new Lock();
   …
   void withdraw(int amount) {
      lk.lock(); // may block
      int b = getBalance();
      if(amount > b){ lk.unlock();
         throw new WithdrawTooLargeException();}
      setBalance(b – amount);
      lk.unlock();
   }
   // deposit would also acquire/release lk
}
```

One lock for each account

Possible mistakes

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.unlock(); // 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

```
public void setBalance(int x) { ..  }

public int getBalance() { ..  }

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

public void deposit(int amount){
        ..
        b = getBalance()
        ..
        setBalance(b + amount);
        ..
}
```

Re-acquiring locks?

One approach:

Can't let outside world call **`setBalance1`**

Can't have **`withdraw`** call **`setBalance2`**

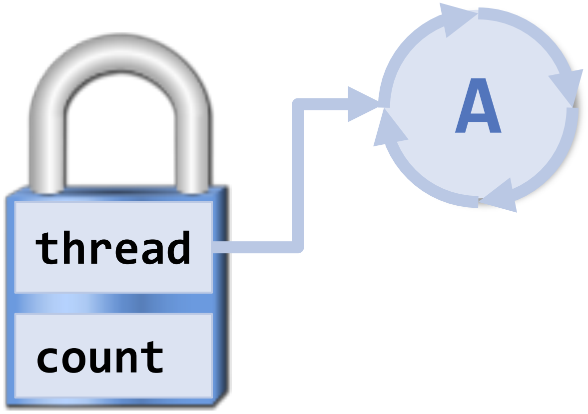
Another approach:

Can modify the meaning of the Lock to support *re-entrant locks*

- Java does this
- Then just use **`setBalance2`**

```
int setBalance1(int x) {
  balance = x;
}
int setBalance2(int x) {
  lk.lock();
  setBalance1(x);
  lk.unlock();
}
void withdraw(int amount) {
  lk.lock();
  …
  setBalance1(b – amount);
  lk.unlock();
}
```

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 **`lock(acquire)`**:

- it does not block
- it increments the count

On **`unlock(release)`**:

- if the count is > 0, the count is decremented
- if the count is 0, the lock becomes *not-held*

Re-entrant locks work

- This simple code works fine provided **`lk`** is a reentrant lock
- Okay to call **`setBalance`** directly
- Okay to call **`withdraw`** (won't block forever)

```
int setBalance(int x) {
  lk.lock();   +1
  balance = x;
  lk.unlock(); -1
}

void withdraw(int amount) {
  lk.lock();   +1
  …
  setBalance(b – amount);
  lk.unlock(); -1
}
```

Now some Java (a bit of recap)

Java has built-in support for re-entrant locks

- Several differences from our pseudocode
- Focus on the **synchronized** statement

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

1. Evaluates *expression* to an object
   Every object "is a lock" in Java (but not primitive types)

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.

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 *conditional variables* (future lectures)

Java provides many other features and details. See, for example:

- Java "Concurrency in Practice" by Goetz et al
- Chapter 30 of "Introduction to Java Programming" by Daniel Liang
- Chapter 14 of "CoreJava", Volume 1 by Horstmann/Cornell

Java synchronized	Java Lock API
use synchronized when possible	
• clean code • easy to maintain • easy to avoid bugs	• try.. finally • error-prone
Scope: cannot go beyond method	Scope: range from one to another method
	fine-grained control
thread is blocked	trylock() → avoids unrestricted waiting
	lockInterruptibly() → a thread can interrupt a waiting thread

Races

Roughly: a race condition occurs when the computation result depends on the scheduling (how threads are interleaved)

Bugs that exist only due to concurrency

No interleaved scheduling with only one *thread* [no concurrency]

[But interleaved scheduling with only one processor *is* possible!]

Typically, problem is some *intermediate state* that "messes up" a concurrent thread that "sees" that state

Note: This lecture makes 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

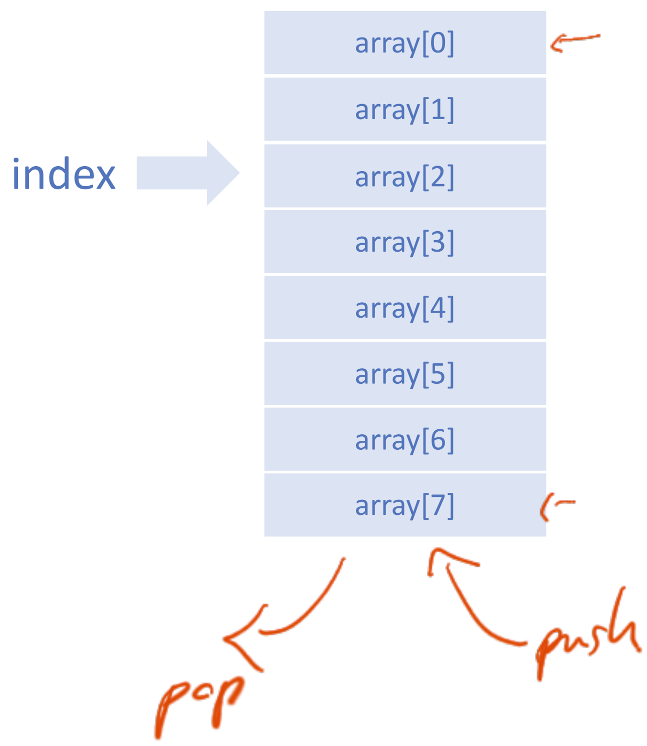
Example: Bounded Stack

```
class StackFullException extends Exception {}
class StackEmptyException extends Exception {}

public class Stack <E> {
E[] array;
int index;

    public Stack(int entries){
        // hack to generate a generic array, initialized with NIL values
        array = (E[]) new Object[entries];
        index = 0;
    }
...

}
```

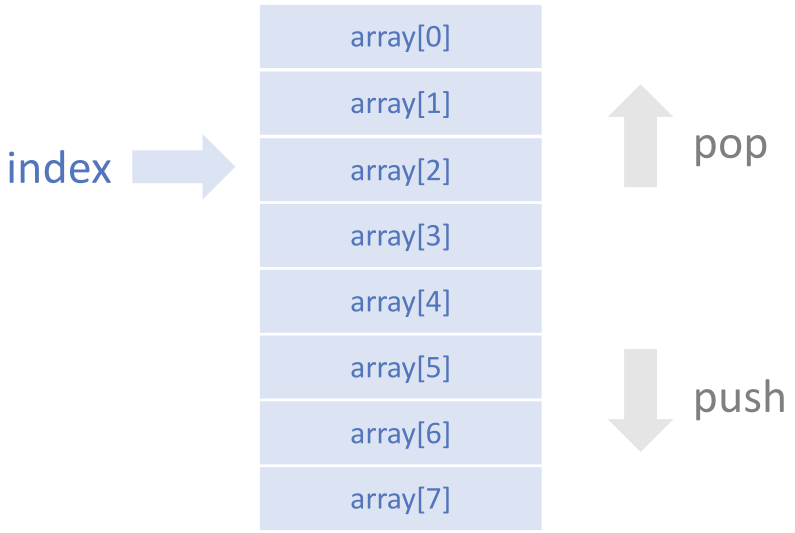


Example: Bounded Stack

```
public class Stack <E> {
…
    synchronized boolean isEmpty() {
        return index==0;
    }

    synchronized void push(E val) throws StackFullException {
        if (index==array.length)
            throw new StackFullException();
        array[index++] = val;
    }

    synchronized E pop() throws StackEmptyException {
        if (index==0) throw new StackEmptyException();
        return array[--index];
    }
}
```



Peek ?

```
public class Stack <E> {
...

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

wrong !

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

`peek`, concurrently speaking

`peek` has no *overall* effect on the shared data

It is a "reader" not a "writer"

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

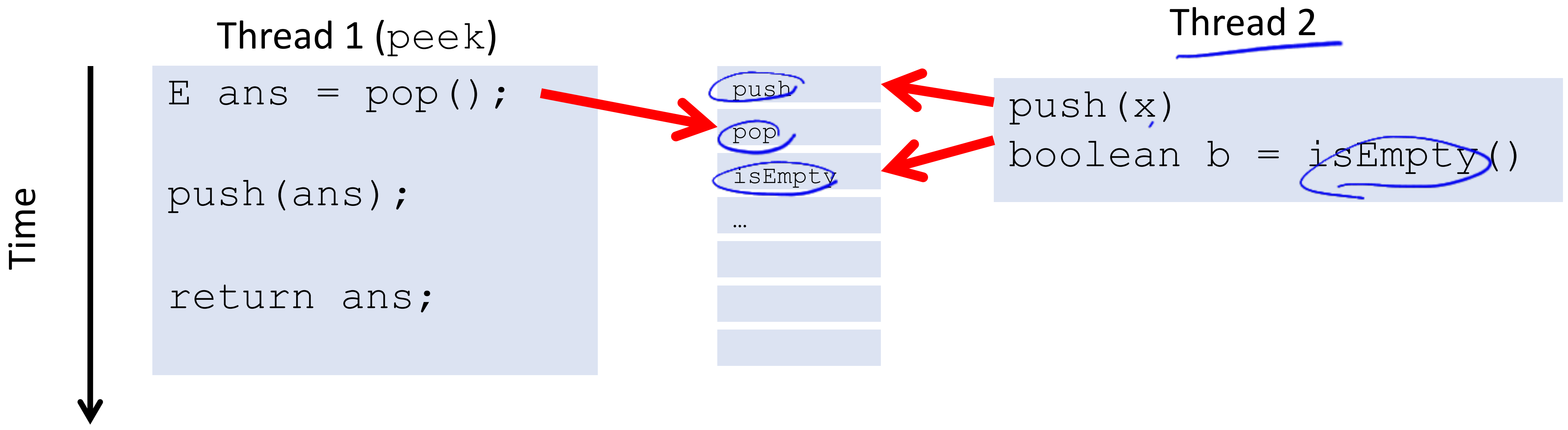
This intermediate state should not be exposed

Leads to several *bad interleavings*

peek and isEmpty

Property we want: If there has been a **`push`** and no **`pop`**, then **`isEmpty`** returns **`false`**

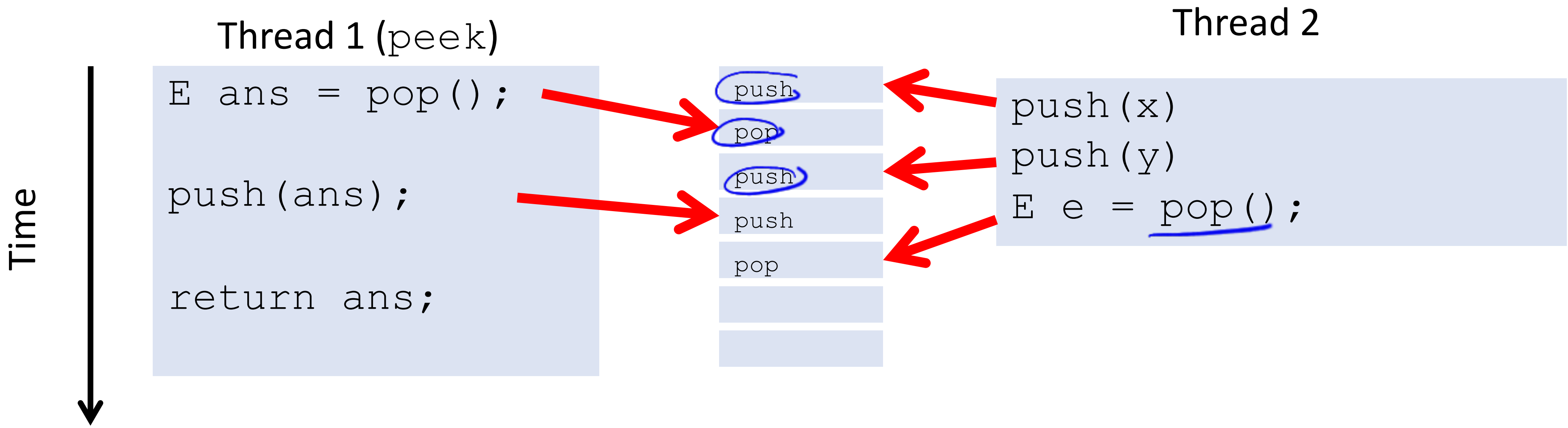
With **`peek`** as written, property can be violated



peek and LIFO

Property we want: Values are returned from **`pop`** in LIFO order

With **`peek`** as written, property can be violated



peek and LIFO

Property we want: Values are returned from **`pop`** in LIFO order

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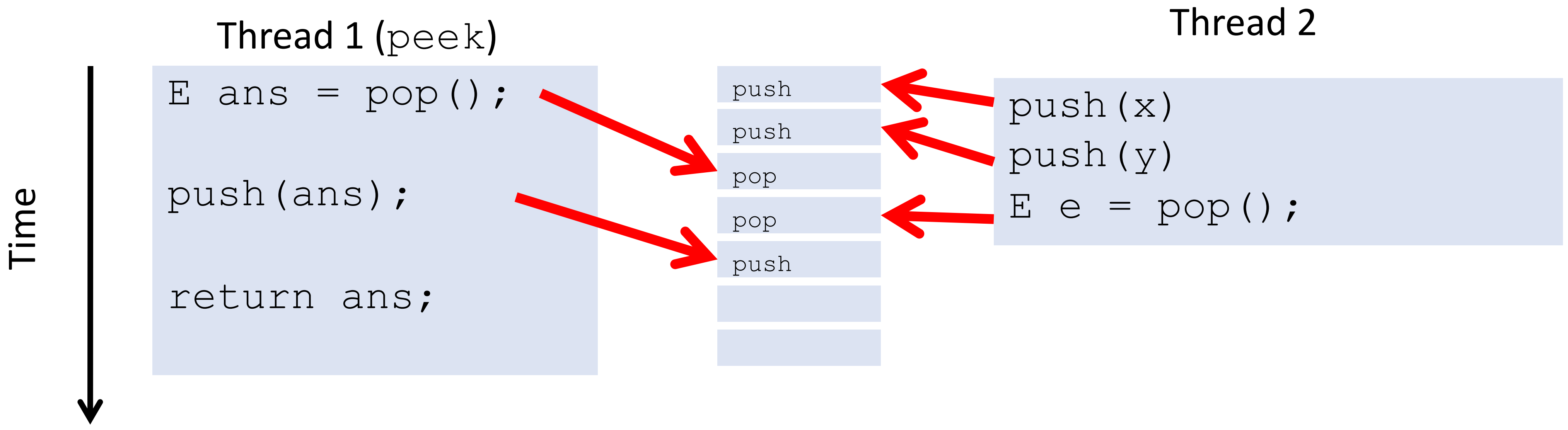


The fix

In short, **`peek`** needs synchronization to disallow interleavings

- The key is to make a *larger critical section*
- Re-entrant locks allow calls to **`push`** and **`pop`**

```
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"

```
boolean isEmpty() {
   return index==0;
}
```

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`**…

The distinction

Data Race [aka *Low Level Race Condition, low semantic level*]
Erroneous program behavior caused by insufficiently synchronized accesses of a shared resource by multiple threads, e.g. Simultaneous read/write or write/write of the same memory location

(for mortals) **always** an error, due to compiler & HW

Original **`peek`** example has no data races

Bad Interleaving [aka *High Level Race Condition, high semantic level*]
Erroneous program behavior caused by an unfavorable execution order of a multithreaded algorithm that makes use of otherwise well synchronized resources.

"Bad" depends on your specification

Original **`peek`** had several

Getting it right

Avoiding race conditions on shared resources is difficult

- Decades of bugs have led to some *conventional wisdom*: general techniques that are known to work

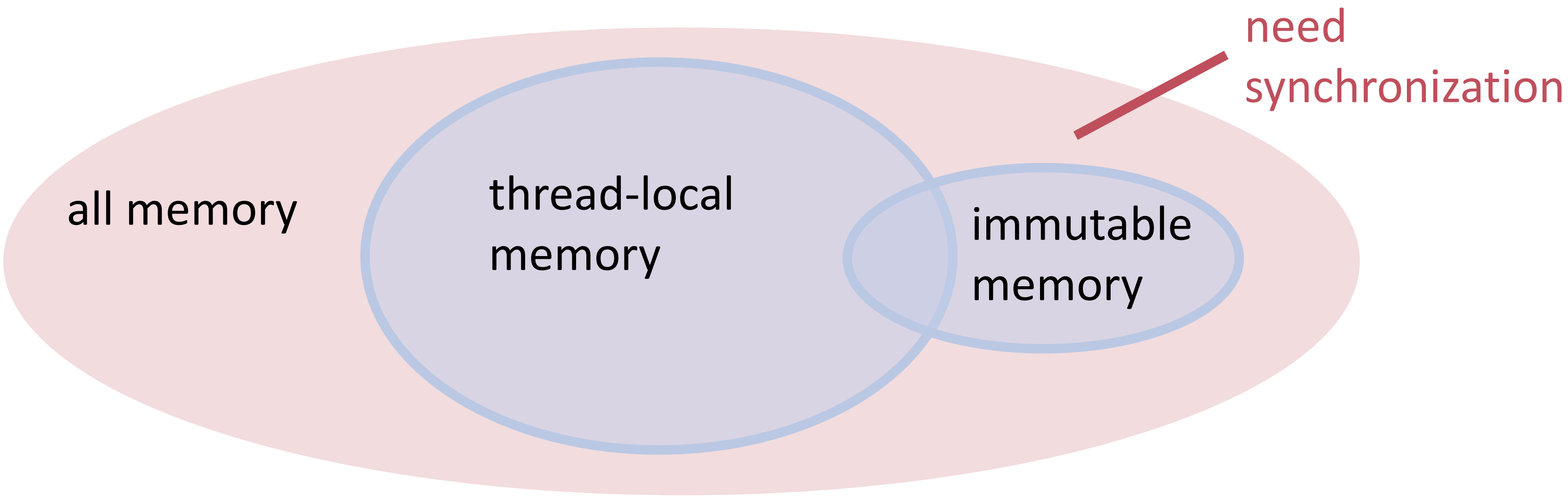
Rest of lecture distills key ideas and trade-offs

- Parts paraphrased from “Java Concurrency in Practice”
- But none of this is specific to Java or a particular book!

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. Synchronized: 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*
  - 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

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. Do not make any assumptions on the orders of reads or writes.

Necessary: In Java or C, a program with a data race is almost always wrong

Not sufficient: Our **`peek`** example had no data races

Consistent Locking

Guideline #1: 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
- Clearly document the guard for each location

In Java, often the guard is the object containing the location

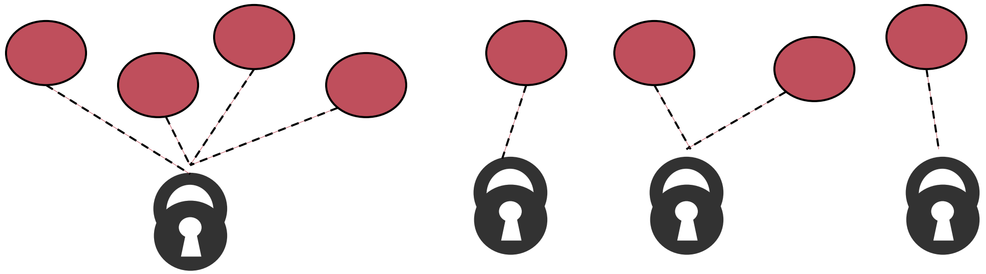
- `this` inside the object's methods
- But also often guard a larger structure with one lock to ensure mutual exclusion on the structure

Consistent Locking continued

The mapping from locations to guarding locks is *conceptual*

- Up to you as the programmer to follow it

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

Beyond consistent locking

Consistent locking is an *excellent guideline*

- A “default assumption” about program design

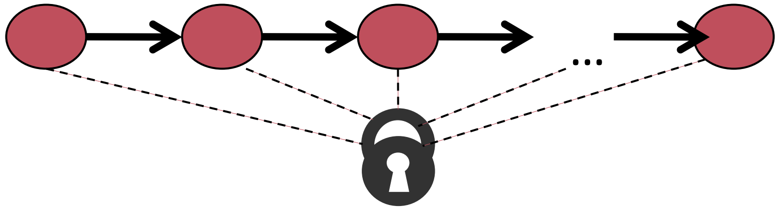
Consistent locking is *not required* for correctness: Can have different program phases use different invariants

- Provided all threads coordinate moving to the next phase

Lock granularity

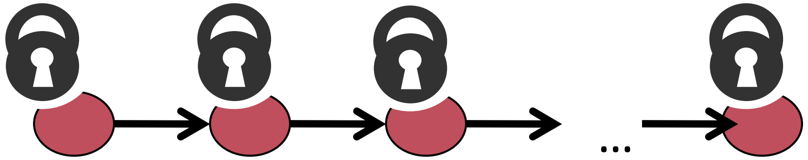
Coarse-grained: Fewer locks, i.e., more objects per lock

- 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: operations that modify data-structure shape

Fine-grained advantages

- More simultaneous access (performance when coarse-grained would lead to unnecessary blocking)

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

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
- Performance loss because of frequent thread switching and cache trashing.

Guideline #3: Do not do expensive computations or I/O in critical sections, but also don't introduce race conditions

Example

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

critical section was too long

(table locked during expensive call)

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

Example

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

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

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

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;
      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*

1) - Make critical sections just long enough to preserve atomicity
2) - *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

It is rare that you should write your own data structure

- Provided in standard libraries

Particularly 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

Practical Guideline: Use built-in libraries whenever they meet your needs

Guideline for this course: do everything to understand it yourself!

- JAVA THREADS : wait, notify, start, join
  synchronized, producer-consumer
  ↳ locks

- PARALLELISM : vectorization, ILP, pipelining,
  latency / throughput

- CONCEPTS : T_1, speedup / efficiency,
  Amdahl / Gustafson
  T_p, T_∞, Task graphs → T_1
  ↳ scheduler

- DIVIDE AND CONQUER : Threads, fork-join, $\underbrace{\text{prefix scan, pack / QS}}_{\text{reduce } T_\infty}$

- low- / HIGH-LEVEL RACES