CSE 332: Data Abstractions

Lecture 21: Programming with Locks and Critical Sections

Ruth Anderson

Winter 2015

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
- 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){ ??? }
}
```

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

Problems with `peek`

- **`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?

Time

Thread 1 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2

```
push(x)
boolean b = isEmpty()
```

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?

Thread 1 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2

```
push(x)
boolean b = isEmpty()
```

Time

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?

Thread 1 (**`peek`**)

```
E ans = pop();
push(ans);
return ans;
```

Thread 2

```
push(x)
boolean b = isEmpty()
```

Time

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?

Thread 1 (`peek`)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2

```
push(x)
push(y)
E e = pop()
```

Time

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?

Time

Thread 1 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2

```
push(x)
push(y)
E e = pop()
```

Example 3: peek and pop

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

Time

Thread 1 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2

```
push(x)
push(y)
E e = pop()
```

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?

Time

Thread 1 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

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?

Time

Thread 1 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2 (**`peek`**)

```
E ans = pop();

push(ans);

return ans;
```

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

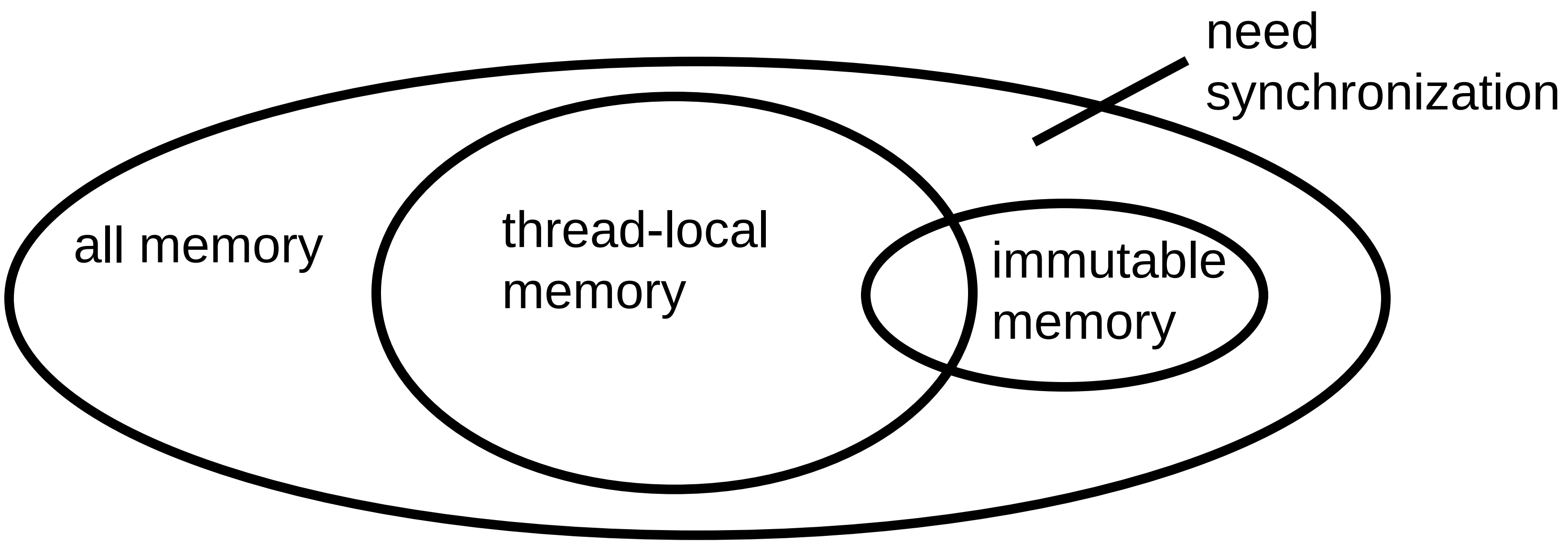
Rest of lecture distills key ideas and trade-offs

- 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

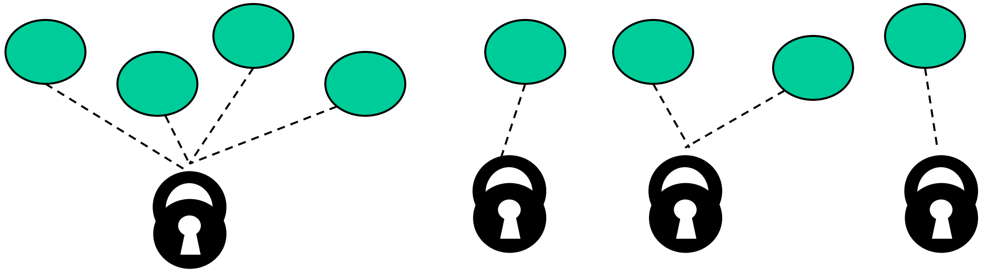
- The same lock can (and often should) guard multiple locations (ex. multiple fields in a class)

- 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…

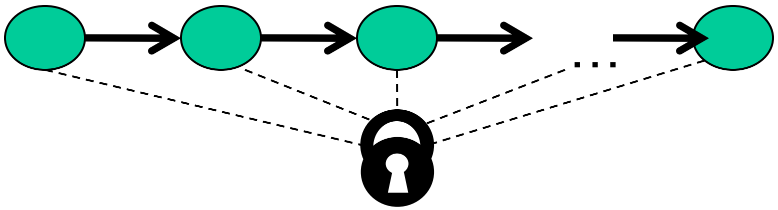
Beyond consistent locking

- 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

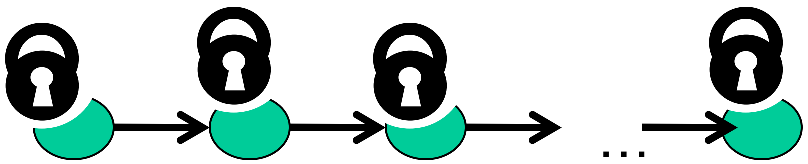
Coarse-grained: Fewer locks, i.e., more objects per lock

- 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 lon**g:

- 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);
  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);
}
```

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*