CSE332: Data Abstractions

Lecture 21: Programming with Locks and Critical Sections

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Announcements

- **Homework 7** – due Friday March 4th at the BEGINNING of lecture!
- **Project 3** – the last programming project!
  - **Version 1 & 2 - Tues March 1, 2011 11PM** - (10% of overall grade)
  - ALL Code - Tues March 8, 2011 11PM - (65% of overall grade):
  - Writeup - Thursday March 10, 2011, 11PM - (25% of overall grade)

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

Races

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; result is that we need to write programs that work independent of scheduling

Race conditions are bugs that exist only due to concurrency
- No interleaved scheduling with 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

Data Races

- A ***data race*** is a specific type of ***race condition*** that can happen in 2 ways:
  - Two different threads can ***potentially*** write a variable at the same time
  - One thread can ***potentially*** write a variable while another reads the variable
  - Simultaneous reads are fine; not a data race, and nothing bad would happen
  - 'Potentially' is important; we say the code itself has a data race – it is independent of an actual execution
- Data races are bad, but we can still have a race condition, and bad behavior, when no data races are present

Stack Example

```
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

```java
class Stack<E> {
  …
  synchronized boolean isEmpty() { … }
  synchronized void push(E val) { … }
  synchronized E pop(E val) {
    if(isEmpty())
      throw new StackEmptyException();
    …
  }
  E peek() {
     E ans = pop();
     push(ans);
     return ans;
  }
}
```

- Maybe we're writing `peek` in an external class that only has access to Stack's `push` and `pop`
- In a sequential world, this code is of questionable *style*, but *correct*

`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:

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

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


Problems with **`peek`**

```java
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's implemented creates an inconsistent *intermediate state*
  - 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; errors can occur

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`**)

```java
E ans = pop();

push(ans);

return ans;
```

Thread 2

```java
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`**
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Thread 1 (**`peek`**)

```java
E ans = pop();

push(ans);

return ans;
```

Thread 2

```java
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?

Time

Thread 1 (**`peek`**)

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

Thread 2

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

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?

Time

Thread 1 (**peek**)

```
E ans = pop();

push(ans);

return ans;
```

Thread 2

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


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 2: peek and pop (again)

- **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 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 3: 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, again (no resizing or checking)

```
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, which may result in strange behavior
    - Compiler optimizations may break it in ways you had not anticipated
    - We'll talk about this more in the future
- Moral: Don't introduce a data race, even if every interleaving you can think of is correct

Getting it right

Avoiding race conditions on shared resources is difficult

- What 'seems fine' in a sequential world can get you into trouble when race conditions are involved
- Decades of bugs has led to some *conventional wisdom*: general techniques that are known to work

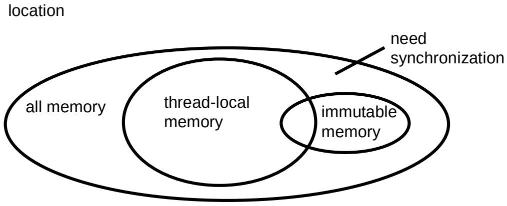
Rest of lecture distills key ideas and trade-offs

- 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!

Pick one of these 3 choices for memory:

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

1. Thread-local: Don't use the location in > 1 thread
2. Immutable: Don't write to the memory location
3. Synchronized: Use synchronization to control access to the location



Thread-local

Whenever possible, don't 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 don't need to communicate through the resource
  - That is, multiple copies are a correct approach
  - Example: **`Random`** objects
- Note: Since 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, don't 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: In Java or C, a 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…

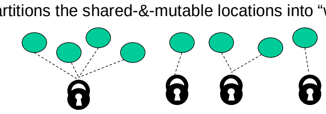
Consistent Locking

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

Consistent Locking (continued)

- The mapping from locations to guarding locks is *conceptual*, and is something that you have to enforce as a programmer
- It partitions the shared-&-mutable locations into "which lock"



Consistent locking is:

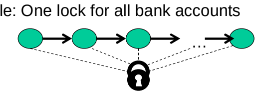
- *Not sufficient*: It prevents all *data* races, but still allows higher-level races (exposed intermediate states)
  - Our **`peek`** example used consistent locking, but had exposed intermediate states (and allowed potential bad interleavings)
- *Not necessary*: Can change the locking protocol dynamically…

Beyond consistent locking…

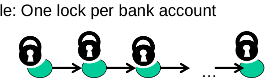
- Consistent locking is an excellent guideline
  - A "default assumption" about program design
  - You will save yourself many a headache using this guideline
- But it isn't required for correctness: Can have different *program phases* use different locking techniques
  - Provided all threads coordinate 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
    - Makes synchronization 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?

Coarse-grained; just grab one lock and proceed

- 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?

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:

- 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: 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

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


Example: 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: 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

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


Example: 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: 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

```
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: 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

- It is rare that you should write your own data structure
  - Provided in standard libraries
  - Point of CSE 332 is to understand the key trade-offs, abstractions and analysis
- 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*