CSE 332: Data Structures and Parallelism

Spring 2022

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Lecture 19: Concurrency and Locks

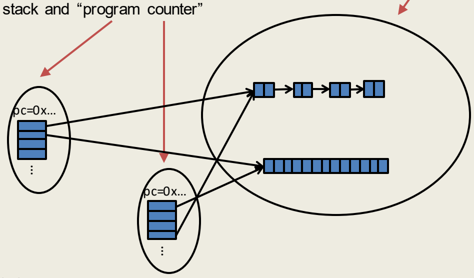
Announcements

- Midterm to be returned Thursday
- Today and Friday - Concurrency

Really sharing memory between Threads

Heap for all objects and static fields, *shared* by all threads

2 Threads, each with own *unshared* call stack and "program counter"



Good sharing

```
class SumTask extends RecursiveTask<Integer> {
  int lo; int hi; int[] arr;
  SumTask(int[] a, int l, int h) { … }
  protected Integer compute(){
    if(hi – lo < SEQUENTIAL_CUTOFF) {
      int ans = 0;
      for (int i=lo; i < hi; i++)
        ans += arr[i];
      return ans;
    }
    else {
      SumTask left = new SumTask(arr,lo,(hi+lo)/2);
      SumTask right= new SumTask(arr,(hi+lo)/2,hi);
      left.fork();
      int rightAns = right.compute();
      int leftAns  = left.join();
      return leftAns + rightAns;
    }
  }
}

static final ForkJoinPool POOL = new ForkJoinPool();
int sum(int[] arr){
   SumTask task = new SumTask(arr,0,arr.length)
   return POOL.invoke(task);
}
```


Banking

- Two threads both trying to `withdraw(100)` from the same account:
- Assume initial `balance` 150

```
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.
}
```

Thread 1

```
x.withdraw(100);
```

Thread 2

```
x.withdraw(100);
```


A bad interleaving

- Interleaved **withdraw(100)** calls on the same account
  - Assume initial **balance == 150**

Time ↓

Thread 1

```
int b = getBalance();
```

Thread 2

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

Thread 1

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

How to fix?

- No way to fix by rewriting the program
  - can always find a bad interleaving -> violation
  - need some kind of synchronization

Time

Thread 1

```
int b = getBalance();



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

Thread 2

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


Race Conditions

A race condition: program executes incorrectly due to unexpected order of threads

data race:
- two threads write a variable at the same time
- one thread writes, another reads simultaneously

bad interleaving: wrong result due to unexpected interleaving of statements in two or more threads

Concurrency

Concurrency:

Correctly and efficiently managing access to shared resources from multiple possibly-simultaneous clients

Requires *coordination*

synchronization to avoid incorrect simultaneous access:

make others *block* (wait) until the resource is free

Concurrent applications are often non-deterministic

how threads are scheduled affects what operations happen first

non-repeatability complicates testing and debugging

must **work for all possible interleavings**!!

Concurrency Examples

- Bank Accounts
- Airline/hotel reservations
- Wikipedia
- Facebook
- Databases

Locks

- Allow access by at most one thread at a time
  - "mutual exclusion"
  - make others *block* (wait) until the resource is free
  - called a **mutual-exclusion lock** or just **lock**, for short
- Critical sections
  - code that requires mutual exclusion
  - defined by the programmer (compiler can't figure this out)

Lock ADT

We define Lock as an ADT 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"* (one thread gets it)
- `release`: makes this lock *"not held"*
  - If >= 1 threads are blocked on it, exactly 1 will acquire it

    Allow access to at most one thread at a time

How can this be implemented?
- acquire (check "not held" -> make "held") **cannot be interrupted**
- special hardware and operating system-level support

Basic idea *(note Lock is not an actual Java class)*

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


Common Mistakes

- Forgetting to release locks
  - e.g., because of Throws (previous slide)
- Too few locks
  - e.g., all bank accounts share a single lock
- Too many locks
  - separate locks for deposit, withdraw

What Do We Lock?

- Class
  - e.g., all bank accounts?
- Object
  - e.g., a particular account?
- Field
  - e.g., balance
- Code fragment
  - e.g., withdraw

Synchronized: *Locks in Java*

Java has built-in support for locks

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

1. *expression* evaluates to an **object**
   - Any **object** (but not primitive types) can be a lock in Java
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.
   - so *impossible* to forget to release the lock

BankAccount in Java

```
class BankAccount {
  private int balance = 0;
  private Object lk = new Object();
  int getBalance()
    { synchronized (lk) { return balance; } }
  void setBalance(int x)
    { synchronized (lk) { balance = x; } }
  void withdraw(int amount) {
      synchronized (lk) {
          int b = getBalance();
          if(amount > b)
              throw …
          setBalance(b – amount);
      }
  }
  // deposit would also use synchronized(lk)
}
```


Shorthand

Usually simplest to use the class object itself as the lock

```
synchronized (this) {
  statements
}
```

This is so common that Java provides a shorthand:

```
synchronized {
  statements
}
```

Final Version

```
class BankAccount {
  private int balance = 0;
  synchronized int getBalance()
    { return balance; }
  synchronized void setBalance(int x)
    { balance = x; }
  synchronized void withdraw(int amount) {
     int b = getBalance();
     if(amount > b)
       throw …
     setBalance(b – amount);
  }
  // deposit would also use synchronized
}
```


Stack Example

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


Why Wrong?

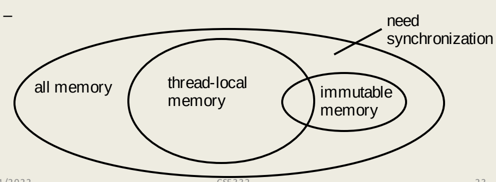
- IsEmpty and push are one-liners. What can go wrong?
  - ans: one line, but multiple operations
  - `array[++index] = val` probably takes at least two ops
  - data race if two pushes happen simultaneously

Stack Example (fixed)

```
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--];
  }
}
```


Lock everything? No.

- For every memory location (e.g., object field), obey at least one of the following:
  1. **Thread-local**: only one thread sees it
  2. **Immutable**: read-only
  3. **Shared-and-mutable**: control access via a lock
  –



Thread local

- Whenever possible, do ***not*** share resources
  - easier to give each thread its own local copy
  - only works if threads don't need to communicate via resource
- In typical concurrent programs, the vast majority of objects should be thread local: shared memory should be rare—minimize it

Immutable

- If location is read-only, no synchronizatin is necessary
- Whenever possible, do ***not*** update objects
  – make new objects instead!
  – one of the key tenets of *functional programming* (CSE 341)
- In practice, programmers usually over-use mutation – minimize it

The rest: keep it synchronized

Other Forms of Locking in Java

- Java provides many other features and details. See, for example:
  – Chapter 14 of CoreJava, Volume 1 by Horstmann/Cornell
  – Java Concurrency in Practice by Goetz et al

Recall Bank Account Problem

```
class BankAccount {
  private int balance = 0;
  synchronized int getBalance()
    { return balance; }
  synchronized void setBalance(int x)
    { balance = x; }
  synchronized void withdraw(int amount) {
     int b = getBalance();
     if(amount > b)
       throw …
     setBalance(b – amount);
  }
  // deposit would also use synchronized
}
```

Call to setBalance in withdraw

- tries to lock **this**

Re-Entrant Lock

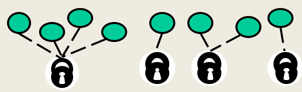
- A re-entrant lock (a.k.a. recursive lock)
  - If a thread holds a lock, subsequent attempts to acquire the **same lock** in the **same thread** won't block
  - **withdraw** can acquire the lock and **setBalance** can also acquire it
  - implemented by maintaining a count of how many times each lock is acquired in each thread, and decrementing the count on each release.
- Java **synchronize** locks are re-entrant

Locking Guidelines

- Correctness
- Consistency: make it well-defined
- Granularity: coarse to fine
- Critical Sections: make them small, atomic
- Leverage libraries

Consistent Locking

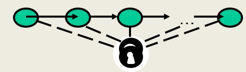
- Clear mapping of locks to resources
  - followed by all methods
  - clearly documented
  - same lock can guard multiple resources



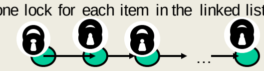
  - what's a resource? Conceptual:
    - object
    - field
    - data structure (e.g., linked list, hash table)

Lock Granularity

- Coarse grained: fewer locks, more objects per lock
  - e.g., one lock for entire data structure (e.g., linked list)



  - advantage:
  - disadvantage:
- Fine grained: more locks, fewer objects per lock
  - e.g., one lock for each item in the linked list



Lock Granularity

•Example: hashtable with separate chaining
  - coarse grained: one lock for whole table
  - fine grained: one lock for each bucket

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

•Which makes implementing **`resize`** easier?

•Suppose hashtable maintains a **`numElements`** field. Which locking approach is better?

Critical Sections

- Critical sections:
  - how much code executes while you hold the lock?
  - want critical sections to be short
  - make them "atomic": think about smallest sequence of operations that have to occur at once (without data races, interleavings)

Critical Sections

- Suppose we want to change a value in a hash table
  - assume one lock for the entire table
  - computing the new value takes a long time ("expensive")

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


Critical Sections

- Suppose we want to change a value in the hash table
  - assume one lock for the entire table
  - computing the new value takes a long time ("expensive")
  - will this work?

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

Critical Sections

- Suppose we want to change a value in the hash table
  - assume one lock for the entire table
  - computing the new value takes a long time (“expensive”)
  - convoluted fix:

```
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);
}}}
```