CSE 332: Data Abstractions

Lecture 20: Shared-Memory Concurrency & Mutual Exclusion

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Toward sharing resources (memory)

So far, we have been studying parallel algorithms using the fork-join model

- Reduce span via parallel tasks

Fork-Join algorithms all had a very simple *structure* to avoid race conditions

- Each thread had memory "only it accessed"
  - Example: each array sub-range accessed by only one thread
- Result of forked process not accessed until after join() called
- So the structure (mostly) ensured that bad simultaneous access wouldn't occur

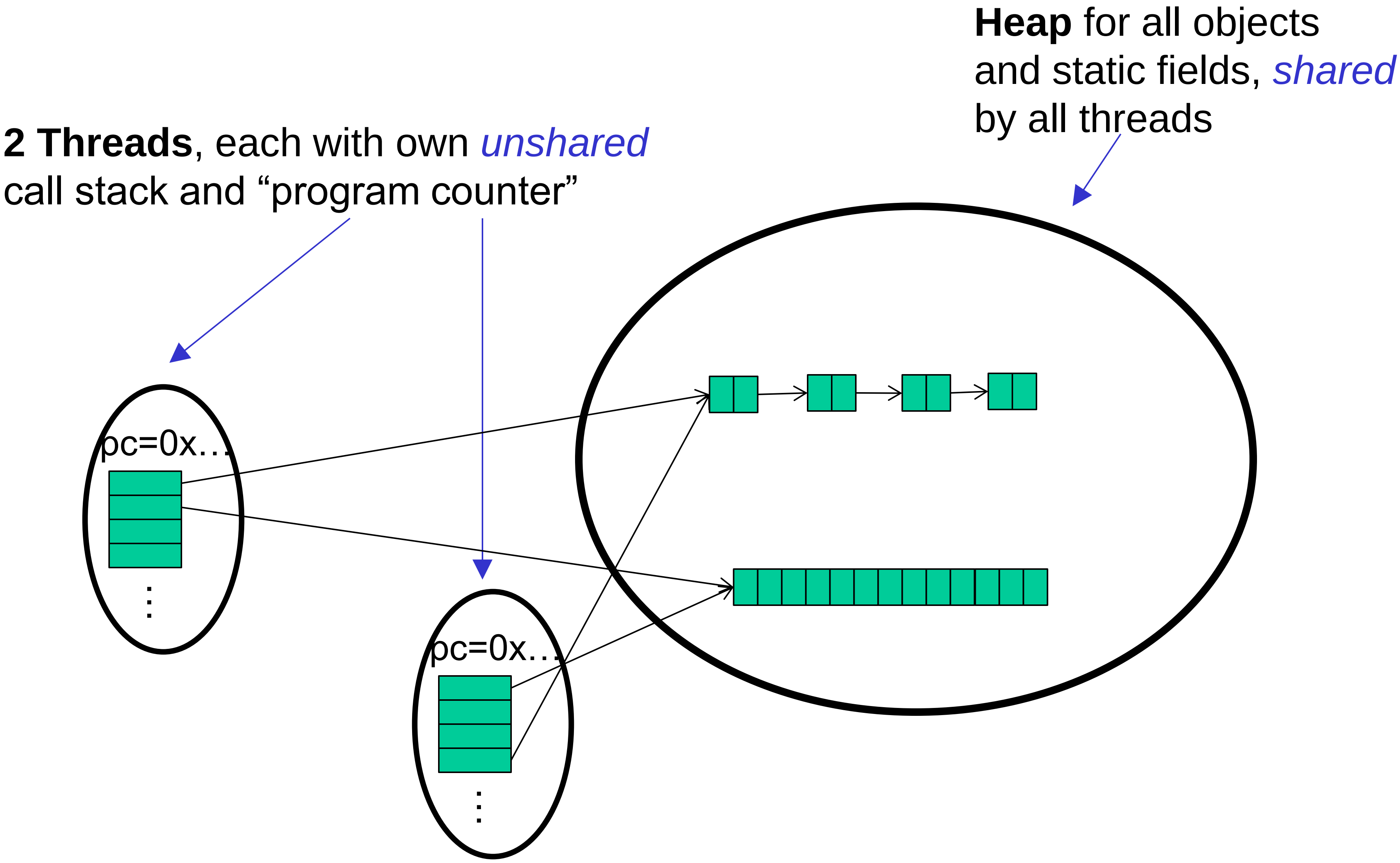
Strategy won't work well when:

- Memory accessed by threads is overlapping or unpredictable
- Threads are doing independent tasks needing access to same resources (rather than implementing the same algorithm)

Each thread accesses a different sub-range of the array: Array is shared, but no overlap

```
class SumArray extends RecursiveTask<Integer> {
  int lo; int hi; int[] arr;//fields to know what to do
  SumArray(int[] a, int l, int h) { … }
  protected Integer compute(){// return answer
    if(hi - lo < SEQUENTIAL_CUTOFF) {
      int ans = 0;
      for(int i=lo; i < hi; i++)
        ans += arr[i];
      return ans;
    } else {
      SumArray left = new SumArray(arr,lo,(hi+lo)/2);
      SumArray right= new SumArray(arr,(hi+lo)/2,hi);
      left.fork();
      int rightAns = right.compute();
      int leftAns  = left.join();
      return leftAns + rightAns;
    }
  }
}
static final ForkJoinPool fjPool = new ForkJoinPool();
int sum(int[] arr){
  return fjPool.invoke(new SumArray(arr,0,arr.length));
}
```

Really sharing memory between Threads



Sharing a Queue….

- Imagine 2 threads, running at the same time,
- both with access to a shared linked-list based queue (initially empty)

```
enqueue(x) {
   if(back==null){
        back=new Node(x);
        front=back;
   }
   else{
        back.next = new Node(x);
        back = back.next;
   }
}
```

Sharing a Queue….

- Imagine 2 threads, running at the same time, both with access to a shared linked-list based queue (initially empty)

```
enqueue(x) {
   if(back==null){
        back=new Node(x);
        front=back;
   }
   else{
        back.next = new Node(x);
        back = back.next;
   }
}
```

- Each thread has own program counter (and local stack)
- Queue is shared, so both threads indirectly use the same ‘front’ and ‘back’ (which is the whole point of sharing the queue)
- We have no guarantee what happens first between different threads; can (and will) arbitrarily ‘interrupt’ each other
- Many things can go wrong: say, one tries to enqueue “a”, the other “b”, and both verify that back is ‘null’ before other sets back
  - Result: One assignment of back will be ‘forgotten’
- In general, any ‘interleaving’ of results is possible if enqueue were called at the same time for both

Concurrent Programming

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

Requires *coordination*, particularly synchronization to avoid incorrect simultaneous access: make somebody *block* (wait) until the resource is free

- **`join`** is not what we want
- Want to block until another thread is "done using what we need" not "completely done executing"

Even correct concurrent applications are usually highly non-deterministic

- how threads are scheduled affects what operations happen first
- non-repeatability complicates testing and debugging

Concurrency Examples

What if we have multiple threads:

1. Processing different bank-account operations
   – What if 2 threads change the same account at the same time?

2. Using a shared cache (e.g., hashtable) of recent files
   – What if 2 threads insert the same file at the same time?

3. Creating a pipeline (think assembly line) with a queue for handing work from one thread to next thread in sequence?
   – What if enqueuer and dequeuer adjust a circular array queue at the same time?

Why threads?

Unlike parallelism, not about implementing algorithms faster

But threads still useful for:

- *Code structure for responsiveness*
  - Example: Respond to GUI events in one thread while another thread is performing an expensive computation
- *Processor utilization (mask I/O latency)*
  - If 1 thread "goes to disk," have something else to do
- *Failure isolation*
  - Convenient structure if want to *interleave* multiple tasks and do not want an exception in one to stop the other

Sharing, again

It is common in concurrent programs that:

- Different threads might access the same resources in an unpredictable order or even at about the same time

- Program correctness requires that simultaneous access be prevented using synchronization

- Simultaneous access is rare
  – Makes testing difficult
  – Must be much more disciplined when designing / implementing a concurrent program
  – Will discuss common idioms known to work

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.
}
```

Interleaving

Suppose:

- Thread **T1** calls **`x.withdraw(100)`**
- Thread **T2** calls **`y.withdraw(100)`**

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

- Could happen even with one processor since a thread can be pre-empted at any point for time-slicing
  - e.g. T1 runs for 50 ms, pauses somewhere, T2 picks up for 50ms

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…

What is the balance at the end?

Two threads both trying to **`withdraw(25)`** from the same account:

- Assume initial **`balance`** 100

```
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(25);
```

Thread 2

```
x.withdraw(25);
```

A bad interleaving

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

- Assume initial **`balance == 150`**
- This ***should*** cause a **`WithdrawTooLarge`** exception

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);
```

A bad fix, Another bad interleaving

Two threads both trying to **`withdraw(100)`** from the same account:

- Assume initial **`balance`** 150
- This ***should*** cause a **`WithdrawTooLarge`** exception

Thread 1

```
int b = getBalance();



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

Thread 2

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

Time

Still a bad fix, Another bad interleaving

Two threads both trying to **`withdraw(100)`** from the same account:

- Assume initial **`balance`** 150
- This ***should*** cause a **`WithdrawTooLarge`** exception

Time ↓

Thread 1

```
int b = getBalance();



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

Thread 2

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

setBalance(getBalance() –
                amount);
```

In all 3 of these examples, instead of an exception, we have a “Lost withdraw”

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);
}
```

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

The 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, areas of code that are mutually exclusive, (which technically have other requirements)

Programmer (you!) must implement critical sections

- "The compiler" has no idea what interleavings should or should not be allowed in your program
- Buy you need language primitives to do it!

Why is this Wrong?

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

- Say we tried to coordinate it ourselves using a boolean variable – "`busy`"
- 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
}
```

`Busy` is initially = false

Still 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" – unhappy bank

Time does elapse between checking 'busy' and setting 'busy'; can be interrupted there

What we need

- There are many ways out of this conundrum, but we need help from the language
- One basic solution: Locks
  - Still on a conceptual level at the moment, 'Lock' is not a Java class (though Java's approach is similar)
- We will 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"* [all at once!]
    - Checking & setting happen together, and cannot be interrupted
    - Fixes problem we saw before!!
  - **`release`**: makes this lock *"not held"*
    - If >= 1 threads are blocked on it, exactly 1 will acquire it

Why that works

- A Lock ADT with operations **`new`**, **`acquire`**, **`release`**

- The lock implementation ensures that given simultaneous acquires and/or releases, a correct thing will happen
  - Example:
    - If we have 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
  - In CSE 332, we take this as a primitive and use it

Note: ‘Lock’ is not an actual Java class

Almost-correct pseudocode

```
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
}
```

Some mistakes

- A lock is a very primitive mechanism
  - Still up to you to use correctly to implement critical sections
- **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.release(); // 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

One (not very good) possibility

```
int setBalance1(int x) {
  balance = x;
}
int setBalance2(int x) {
  lk.acquire();
  balance = x;
  lk.release();
}
void withdraw(int amount) {
  lk.acquire();
  …
  setBalance1(b - amount);
  lk.release();
}
```

Have two versions of setBalance!

- `withdraw` calls `setBalance1` (since it already has the lock)
- Outside world calls `setBalance2`
- Could work (if adhered to), but not good style; also not very convenient
- Alternately, we can modify the meaning of the Lock ADT to support ***re-entrant locks***
  - Java does this
  - Then just always use `setBalance2`

Re-entrant lock idea

A re-entrant lock (a.k.a. recursive lock)

- **The idea**: Once acquired, the lock is held by the Thread, and subsequent calls to **`acquire`** *in that Thread* won't block

- **Result**: **`withdraw`** can acquire the lock, and then call **`setBalance`**, which can also acquire the lock
  - Because they're in the same thread & it's a re-entrant lock, the inner **`acquire`** won't block!!

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 **`acquire`** :
  - it does not block
  - it increments the count
- On **`release`** :
  - if the count is > 0, the count is decremented
  - if the count is 0, the lock becomes *not-held*

Re-entrant locks work

```
int setBalance(int x) {
  lk.acquire();
  balance = x;
  lk.release();
}

void withdraw(int amount) {
  lk.acquire();
  …
  setBalance(b – amount);
  lk.release();
}
```

This simple code works fine provided **lk** is a reentrant lock

- Okay to call **setBalance** directly
- Okay to call **withdraw** (won't block forever)

Java's Re-entrant Lock

- **`java.util.concurrent.locks.ReentrantLock`**
- Has methods **`lock()`** and **`unlock()`**
- As described above, it is conceptually owned by the Thread, and shared within that thread
- Important to guarantee that lock is ***always*** released!!!
- Recommend something like this:

```
myLock.lock();
try { // method body }
finally { myLock.unlock(); }
```

- Despite what happens in 'try', the code in finally will execute afterwards

`Synchronized`: *A Java convenience*

Java has built-in support for re-entrant locks

– You can use the **`synchronized`** statement as an alternative to declaring a **`ReentrantLock`**

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

1. Evaluates *expression* to an **object**
   - Every **object** (but not primitive types) "is 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

Java version #1 (correct but can be improved)

```
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)
}
```

Improving the Java

- As written, the lock is **private**
  - Might seem like a good idea
  - But also prevents code in other classes from writing operations that synchronize with the account operations

- More idiomatic is to synchronize on `this`…
  - Also more convenient: no need to have an extra object!

Java version #2

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

Syntactic sugar

Version #2 is slightly poor style because there is a shorter way to say the same thing:

Putting **synchronized** before a method declaration means the entire method body is surrounded by

```
synchronized(this){…}
```

Therefore, version #3 (next slide) means exactly the same thing as version #2 but is more concise

Java version #3 (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
}
```

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 *condition variables* (future lecture)

- 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