CSE332: Data Abstractions

Lecture 20: Mutual Exclusion and Locking

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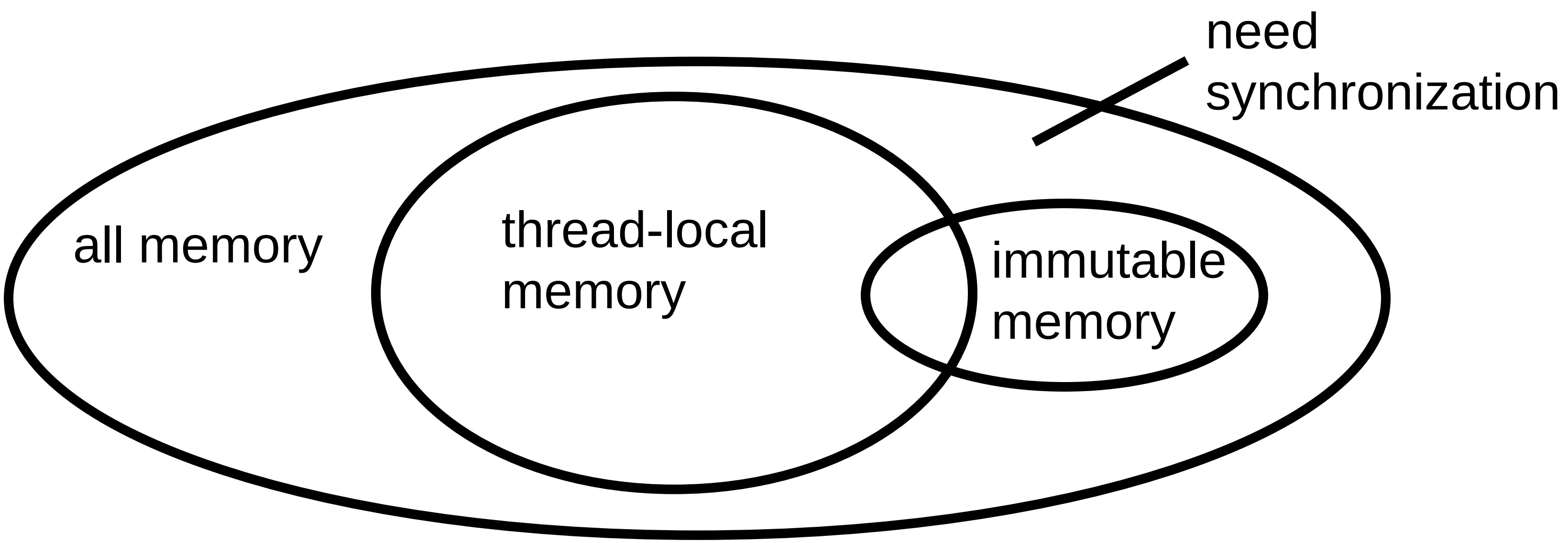
Pick From These 3 Choices for Memory:

For every memory location in your program (e.g., object field), 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



Thread-Local

Whenever possible, do not share resources

- Easier for each thread have its own thread-local *copy* of a resource instead of one with shared updates
- Correct only if threads do not communicate through resource
  - In other words, 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 usage should be minimized

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, no synchronization needed

- Simultaneous reads are *not* races and *not* a problem

In practice, programmers usually over-use mutation – minimize it

Everything Else: Keep it Synchronized

After minimizing the amount of memory that is both (1) thread-shared and (2) mutable, we need guidelines for how to use locks to keep that data consistent

Guideline #0: No data races

- Never allow two threads to read/write or write/write the same location at the same time

Necessary:

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

But Not Sufficient:

Our **`peek`** example had no data races

Consistent Locking

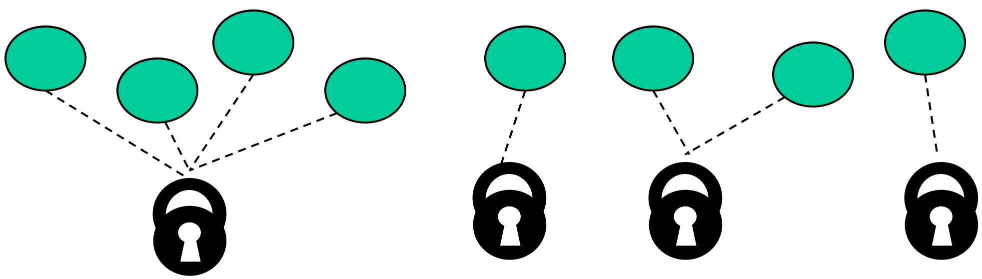
Guideline #1: Consistent Locking

For each location that requires 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 guard multiple locations (and often should)
- Clearly document the guard for each location
- In Java, the guard is often the object containing the location
  - **`this`** inside object methods
  - But also common to guard a larger structure
    with one lock to ensure mutual exclusion on the structure

Consistent Locking

- The mapping from locations to guarding locks is *conceptual,* and must be enforced by you as the programmer
- It partitions the shared-&-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 had exposed intermediate states and bad interleavings

Not Necessary:

Can dynamically change the locking protocol

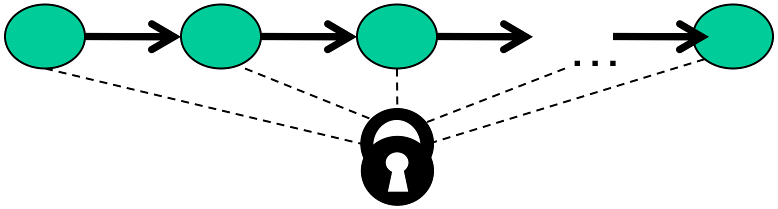
Beyond Consistent Locking

- Consistent locking is an excellent guideline
  - A "default assumption" about program design
  - You will save yourself many a headache using this guideline
- But it is not required for correctness:
  Different *program phases* can 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 (i.e., thread local)
  - And later the grid is only read in response to queries
    - Makes synchronization doubly unnecessary (i.e., immutable)

Lock Granularity

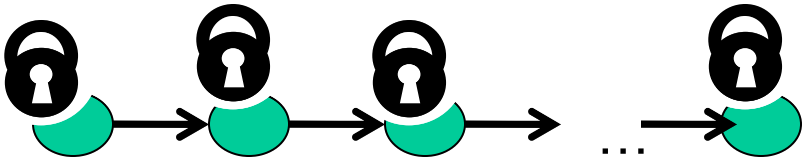
Coarse-Grained: Fewer locks (i.e., more objects per lock)

- 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 to implement modifications of data-structure shape

Fine-grained advantages

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

Guideline #2: Lock Granularity

Start with coarse-grained (simpler), move to fine-grained (performance) only if *contention* on coarse locks is an issue. Alas, often leads to bugs.

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?

Maintaining a **`numElements`** field will destroy the potential benefits of using separate locks for each bucket, why?

Updating it each insert w/o a coarse 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: Granularity

Do not do expensive computations or I/O in critical sections, but also do not introduce race conditions

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

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

(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

(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: Atomicity

- Think in terms of what operations need to be *atomic*
- Make critical sections just long enough to preserve atomicity
- *Then* design locking protocol to implement the critical sections

In other words:

Think about atomicity first and locks second

Do Not Roll Your Own

- It is rare that you should write your own data structure
  - Excellent implementations provided in standard libraries
  - Point of CSE 332 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: Libraries

Use built-in libraries whenever they meet your needs

Motivating Memory-Model Issues

Tricky and *surprisingly wrong* unsynchronized concurrent code

```
class C {
  private int x = 0;
  private int y = 0;

  void f() {
    x = 1;
    y = 1;
  }
  void g() {
    int a = y;
    int b = x;
    assert(b >= a);
  }
}
```

First understand why it looks like the assertion cannot fail:

- Easy case: call to **`g`** ends before any call to **`f`** starts
- Easy case: at least one call to **`f`** completes before call to **`g`** starts
- If calls to **`f`** and **`g`** *interleave*…

Interleavings are Not Enough

There is no interleaving of **`f`** and **`g`** where the assertion fails

- Proof #1: Exhaustively consider all possible orderings of access to shared memory (there are 6)
- Proof #2:
  If **`!(b>=a)`**, then **`a==1`** and **`b==0`**.
  But if **`a==1`**, then **`y=1`** happened before **`a=y`**.
  Because programs execute in order:
  `a=y` happened before **`b=x`** and **`x=1`** happened before **`y=1`**.
  So by transitivity, **`b==1`**. Contradiction.

Thread 1: **`f`**

```
x = 1;

y = 1;
```

Thread 2: **`g`**

```
int a = y;

int b = x;

assert(b >= a);
```

Wrong

However, the code has a *data race*

- Unsynchronized read/write or write/write of same location

If code has data races, you cannot reason about it with interleavings

- This is simply the rules of Java (and C, C++, C#, other languages)
- Otherwise we would slow down all programs just to “help” those with data races, and that would not be a good engineering trade-off
- So the assertion can fail

Why

For performance reasons, the compiler and the hardware will often reorder memory operations

- Take a compiler or computer architecture course to learn more

Thread 1: **`f`**

```
x = 1;

y = 1;
```

Thread 2: **`g`**

```
int a = y;

int b = x;

assert(b >= a);
```

Of course, we cannot just let them reorder anything they want

- Each thread computes things by executing code in order
- Consider: **`x=17; y=x;`**

The Grand Compromise

The compiler/hardware will never perform a memory reordering that affects the result of a single-threaded program

The compiler/hardware will never perform a memory reordering that affects the result of a data-race-free multi-threaded program

So: If no interleaving of your program has a data race,
then you can *forget about all this reordering nonsense:*
the result will be equivalent to some interleaving

Your job: Avoid data races

Compiler/hardware job: Give illusion of interleaving *if you do your job*

Fixing Our Example

- Naturally, we can use synchronization to avoid data races
  - Then, indeed, the assertion cannot fail

```
class C {
  private int x = 0;
  private int y = 0;
  void f() {
    synchronized(this) { x = 1; }
    synchronized(this) { y = 1; }
  }
  void g() {
    int a, b;
    synchronized(this) { a = y; }
    synchronized(this) { b = x; }
    assert(b >= a);
  }
}
```

A Second Fix: Stay Away from This

- Java has **`volatile`** fields: accesses do not count as data races
  - But you cannot read-update-write

```
class C {
  private volatile int x = 0;
  private volatile int y = 0;
  void f() {
    x = 1;
    y = 1;
  }
  void g() {
    int a = y;
    int b = x;
    assert(b >= a);
  }
}
```

- Implementation: slower than regular fields, faster than locks
- Really for experts: avoid them; use standard libraries instead
- And why do you need code like this anyway?

Code That is Wrong

- Here is a more realistic example of code that is wrong
  - No *guarantee* Thread 2 will *ever* stop (as there is a data race)
  - But honestly it will "likely work in practice"

```
class C {
  boolean stop = false;
  void f() {
    while(!stop) {
      // draw a monster
    }
  }
  void g() {
    stop = didUserQuit();
  }
}
```

Thread 1: `f()`

Thread 2: `g()`

Motivating Deadlock Issues

Consider a method to transfer money between bank accounts

```
class BankAccount {
  …
  synchronized void withdraw(int amt) {…}
  synchronized void deposit(int amt) {…}
  synchronized void transferTo(int amt,
                               BankAccount a) {
    this.withdraw(amt);
    a.deposit(amt);
  }
}
```

Notice during call to **`a.deposit`**, thread holds two locks

- Need to investigate when this may be a problem

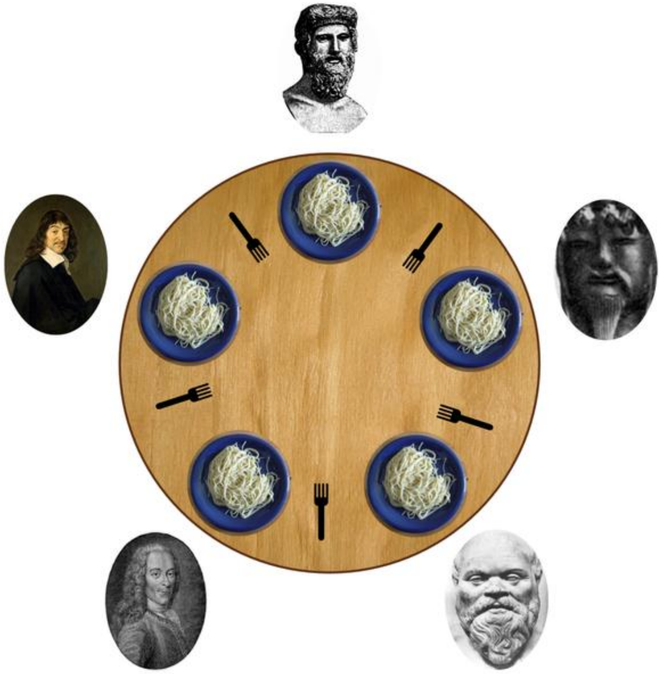
The Deadlock

Suppose **`x`** and **`y`** are fields holding accounts

Time	Thread 1: **`x.transferTo(1,y)`**	Thread 2: **`y.transferTo(1,x)`**
	acquire lock for x	
	do withdraw from x	
		acquire lock for y
		do withdraw from y
		block on lock for x
↓	***block on lock for y***	

The Dining Philosophers

- 5 philosophers go out to dinner together at an Italian restaurant
- Sit at a round table; one fork per setting
- When the spaghetti comes, each philosopher proceeds to grab their right fork, then their left fork, then eats
- ‘Locking’ for each fork results in a ***deadlock***



Deadlock

A deadlock occurs when there are threads **T1**, …, **Tn** such that:

- For **i**=1,..,n-1, **Ti** is waiting for a resource held by **T(i+1)**
- **Tn** is waiting for a resource held by **T1**

In other words, there is a *cycle* of waiting

- – Can formalize as a graph of dependencies with cycles bad

Deadlock avoidance in programming amounts to techniques to ensure a cycle can never arise

Back to Our Example

Options for deadlock-proof transfer:

1. Make a smaller critical section: **`transferTo`** not synchronized
   - Exposes intermediate state after **`withdraw`** before **`deposit`**
   - May be okay, but exposes wrong total amount in bank

2. Coarsen lock granularity:
   one lock for all accounts allowing transfers between them
   - Works, but sacrifices concurrent deposits/withdrawals

3. Give every bank-account a unique number
   and always acquire locks in the same order
   - *Entire program* should obey this order to avoid cycles
   - Code acquiring only one lock can ignore the order

Ordering Locks

```
class BankAccount {
  …
  private int acctNumber; // must be unique
  void transferTo(int amt, BankAccount a) {
    if(this.acctNumber < a.acctNumber)
       synchronized(this) {
       synchronized(a) {
          this.withdraw(amt);
          a.deposit(amt);
       }}
    else
       synchronized(a) {
       synchronized(this) {
          this.withdraw(amt);
          a.deposit(amt);
       }}
  }
}
```

StringBuffer Example

From the Java standard library

```
class StringBuffer {
  private int count;
  private char[] value;
  …
  synchronized append(StringBuffer sb) {
    int len = sb.length();
    if(this.count + len > this.value.length)
      this.expand(…);
    sb.getChars(0,len,this.value,this.count);
  …
  }
  synchronized getChars(int x, int, y,
                        char[] a, int z) {
    "copy this.value[x..y] into a starting at z"
  }
}
```

Two Problems

Problem #1:

Lock for **`sb`** not held between calls to **`sb.length`** and **`sb.getChars`**

- So **`sb`** could get longer
- Would cause **`append`** to throw an **`ArrayBoundsException`**

Problem #2:

Deadlock potential if two threads try to **`append`** in opposite directions, identical to the bank-account first example

Not easy to fix both problems without extra copying:

- Do not want unique ids on every **`StringBuffer`**
- Do not want one lock for all **`StringBuffer`** objects

Actual Java library: fixed neither (left code as is; changed documentation)

- Up to clients to avoid such situations with own protocols

Perspective

- Code like account-transfer and string-buffer append are difficult to deal with for deadlock

- Easier case: different types of objects
  - Can document a fixed order among types
  - Example: "When moving an item from the hashtable to the work queue, never try to acquire the queue lock while holding the hashtable lock"

- Easier case: objects are in an acyclic structure
  - Can use the data structure to determine a fixed order
  - Example: "If holding a tree node's lock, do not acquire other tree nodes' locks unless they are children in the tree"