A Sophomoric Introduction to Shared-Memory Parallelism and Concurrency

Lecture 6
Data Races and Memory Reordering
Deadlock
Readers/Writer Locks
Condition Variables

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For more information, see http://www.cs.washington.edu/homes/djg/teachingMaterials/
Outline

Done:
• Programming with locks and critical sections
• Key guidelines and trade-offs

Now: The other basics an informed programmer needs to know
• Why you must avoid data races (memory reorderings)
• Another common error: Deadlock
• Other common facilities useful for shared-memory concurrency
  – Readers/writer locks
  – Condition variables, or, more generally, passive waiting
Motivating memory-model issues

Tricky and *surprisingly wrong* unsynchronized concurrent code

```java
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*…
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 \(! (b \geq a)\), 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.
Wrong

However, the code has a *data race*
  – Two actually
  – Recall: data race: unsynchronized read/write or write/write of same location

If code has data races, you cannot reason about it with interleavings!
  – That is simply the rules of Java (and C, C++, C#, …)
  – (Else would slow down all programs just to “help” programs with data races, and that was deemed a bad engineering trade-off when designing the languages/compilers/hardware)
  – So the assertion can fail

Recall Guideline #0: No data races
Why

For performance reasons, the compiler and the hardware often reorder memory operations
- Take a compiler or computer architecture course to learn why

Thread 1: f

x = 1;
y = 1;

Thread 2: g

int a = y;
int b = x;
assert(b >= a);

Of course, you cannot just let them reorder anything they want
- Each thread executes in order after all!
- Consider: \texttt{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

```java
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

- Java has **volatile** fields: accesses do not count as data races
- 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?

```java
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);
    }
}
```
Code that’s wrong

- A more realistic example of code that is wrong
  - No guarantee Thread 1 will ever stop even if “user quits”
  - But honestly, it will “likely work in practice”

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

Thread 1: f()
Thread 2: g()
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Motivating Deadlock Issues

Consider a method to transfer money between bank accounts

```java
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

Thread 1: $x.\text{transferTo}(1,y)$
- acquire lock for $x$
- do withdraw from $x$
- block on lock for $y$

Thread 2: $y.\text{transferTo}(1,x)$
- acquire lock for $y$
- do withdraw from $y$
- block on lock for $x$
Deadlock, in general

A deadlock occurs when there are threads $T_1, \ldots, T_n$ such that:

- For $i=1,\ldots,n-1$, $T_i$ is waiting for a resource held by $T_{i+1}$
- $T_n$ is waiting for a resource held by $T_1$

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);
                }
            }
        }
    }
}
Another 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` is 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, just like in 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 javadoc)
  – 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”
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  – Condition variables
Reading vs. writing

Recall:

– Multiple concurrent reads of same memory: *Not* a problem
– Multiple concurrent writes of same memory: Problem
– Multiple concurrent read & write of same memory: Problem

So far:

– If concurrent write/write or read/write might occur, use synchronization to ensure one-thread-at-a-time

But this is unnecessarily conservative:

– Could still allow multiple simultaneous readers!
Example

Consider a hashtable with one coarse-grained lock
- So only one thread can perform operations at a time

But suppose:
- There are many simultaneous `lookup` operations
- `insert` operations are very rare

Note: Important that `lookup` does not actually mutate shared memory, like a move-to-front list operation would
Readers/writer locks

A new synchronization ADT: The readers/writer lock

- A lock’s states fall into three categories:
  - “not held”
  - “held for writing” by one thread
  - “held for reading” by one or more threads

- new: make a new lock, initially “not held”
- acquire_write: block if currently “held for reading” or “held for writing”, else make “held for writing”
- release_write: make “not held”
- acquire_read: block if currently “held for writing”, else make/keep “held for reading” and increment readers count
- release_read: decrement readers count, if 0, make “not held”

\[ 0 \leq \text{writers} \leq 1 \\
0 \leq \text{readers} \\
\text{writers} \times \text{readers} = 0 \]
Pseudocode example (not Java)

class Hashtable<K,V> {
    ...
    // coarse-grained, one lock for table
    RWLock lk = new RWLock();
    V lookup(K key) {
        int bucket = hasher(key);
        lk.acquire_read();
        ...
        read array[bucket] ...
        lk.release_read();
    }
    void insert(K key, V val) {
        int bucket = hasher(key);
        lk.acquire_write();
        ...
        write array[bucket] ...
        lk.release_write();
    }
}
Readers/writer lock details

• A readers/writer lock implementation ("not our problem") usually gives priority to writers:
  – Once a writer blocks, no readers arriving later will get the lock before the writer
  – Otherwise an insert could starve

• Re-entrant?
  – Mostly an orthogonal issue
  – But some libraries support upgrading from reader to writer

• Why not use readers/writer locks with more fine-grained locking, like on each bucket?
  – Not wrong, but likely not worth it due to low contention
In Java

Java’s `synchronized` statement does not support readers/writer

Instead, library

`java.util.concurrent.locks.ReentrantReadWriteLock`

- Different interface: methods `readLock` and `writeLock` return objects that themselves have `lock` and `unlock` methods

- Does *not* have writer priority or reader-to-writer upgrading
  - Always read the documentation
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  – Condition variables
Motivating Condition Variables

To motivate condition variables, consider the canonical example of a **bounded buffer** for sharing work among threads.

Bounded buffer: A queue with a fixed size
- (Unbounded still needs a condition variable, but 1 instead of 2)

For sharing work – think an assembly line:
- Producer thread(s) do some work and enqueue result objects
- Consumer thread(s) dequeue objects and do next stage
- Must synchronize access to the queue
class Buffer\<E\> {  
  E[\[] array = (E[]) new Object[SIZE];  
  ... // front, back fields, isEmpty, isFull methods  
synchronized void enqueue(E elt) {  
    if(isFull())  
      ???  
    else  
      ... add to array and adjust back ...  
  }
  synchronized E dequeue()  
    if(isEmpty())  
      ???  
    else  
      ... take from array and adjust front ...  
}
Waiting

- **enqueue** to a full buffer should *not* raise an exception
  - Wait until there is room

- **dequeue** from an empty buffer should *not* raise an exception
  - Wait until there is data

*Bad approach* is to *spin* (wasted work and keep grabbing lock)

```java
void enqueue(E elt) {
    while(true) {
        synchronized(this) {
            if(isFull()) continue;
            ... add to array and adjust back ... 
            return;
        }
    }
    // dequeue similar

void dequeue() {
    ... if(available() or not empty()) { ... take from array and adjust back ... return;
}
```
What we want

• Better would be for a thread to *wait* until it can proceed
  – Be *notified* when it should try again
  – In the meantime, let other threads run

• Like locks, not something you can implement on your own
  – Language or library gives it to you, typically implemented with
    operating-system support

• An ADT that supports this: *condition variable*
  – Informs waiter(s) when the *condition* that causes it/them to
    wait has *varied*

• Terminology not completely standard; will mostly stick with Java
Java approach: **not quite right**

class Buffer<E> {
    ...
    synchronized void enqueue(E elt) {
        if(isFull())
            this.wait(); // releases lock and waits
        add to array and adjust back
        if(buffer was empty)
            this.notify(); // wake somebody up
    }
    synchronized E dequeue() {
        if(isEmpty())
            this.wait(); // releases lock and waits
        take from array and adjust front
        if(buffer was full)
            this.notify(); // wake somebody up
    }
}
Key ideas

• Java weirdness: every object “is” a condition variable (and a lock)
  – other languages/libraries often make them separate

• wait:
  – “register” running thread as interested in being woken up
  – then atomically: release the lock and block
  – when execution resumes, thread again holds the lock

• notify:
  – pick one waiting thread and wake it up
  – no guarantee woken up thread runs next, just that it is no longer blocked on the condition – now waiting for the lock
  – if no thread is waiting, then do nothing
Bug #1

between the time a thread is notified and it re-acquires the lock, the condition can become false again!

synchronized void enqueue(E elt){
    if(isFull())
        this.wait();
    add to array and adjust back
    ...
}

Between the time a thread is notified and it re-acquires the lock, the condition can become false again!

Thread 1 (enqueue)
    if(isFull())
        this.wait();
    add to array

Thread 2 (dequeue)
    take from array
    if(was full)
        this.notify();

Thread 3 (enqueue)
    make full again
Bug fix #1

```java
synchronized void enqueue(E elt) {
    while(isFull())
        this.wait();
...
}
synchronized E dequeue() {
    while(isEmpty())
        this.wait();
...
}
```

Guideline: *Always* re-check the condition after re-gaining the lock

– In fact, for obscure reasons, Java is technically allowed to notify a thread *spuriously* (i.e., for no reason)
Bug #2

- If multiple threads are waiting, we wake up only one
  - Sure only one can do work *now*, but can’t forget the others!

```java
Thread 1 (enqueue)
while(isFull())
  this.wait();
...

Thread 2 (enqueue)
while(isFull())
  this.wait();
...

Thread 3 (dequeue)
// dequeue #1
if(buffer was full)
  this.notify();

// dequeue #2
if(buffer was full)
  this.notify();
```
Bug fix #2

```java
synchronized void enqueue(E elt) {
    ...
    if(buffer was empty)
        this.notifyAll(); // wake everybody up
}

synchronized E dequeue() {
    ...
    if(buffer was full)
        this.notifyAll(); // wake everybody up
}
```

`notifyAll` wakes up all current waiters on the condition variable

Guideline: If in any doubt, use `notifyAll`
- Wasteful waking is better than never waking up

• So why does `notify` exist?
  - Well, it is faster when correct…
Alternate approach

• An alternative is to call `notify` (not `notifyAll`) on every `enqueue` / `dequeue`, not just when the buffer was empty / full
  – Easy: just remove the `if` statement

• Alas, makes our code subtly wrong since it is technically possible that an `enqueue` and a `dequeue` are both waiting
  – See notes for the step-by-step details of how this can happen

• Works fine if buffer is unbounded since then only dequeuers wait
Alternate approach fixed

• The alternate approach works if the enqueuers and dequeuers wait on different condition variables
  – But for mutual exclusion both condition variables must be associated with the same lock

• Java’s “everything is a lock / condition variable” does not support this: each condition variable is associated with itself

• Instead, Java has classes in java.util.concurrent.locks for when you want multiple conditions with one lock
  – class ReentrantLock has a method newCondition that returns a new Condition object associate with the lock
  – See the documentation if curious
Last condition-variable comments

- `notify/notifyAll` often called `signal/broadcast`, also called `pulse/pulseAll`

- Condition variables are subtle and harder to use than locks

- But when you need them, you need them
  - Spinning and other work-arounds do not work well

- Fortunately, like most things in a data-structures course, the common use-cases are provided in libraries written by experts
  - Example:
    - `java.util.concurrent.ArrayBlockingQueue<E>`
  - All uses of condition variables hidden in the library; client just calls `put` and `take`
Concurrency summary

• Access to shared resources introduces new kinds of bugs
  – Data races
  – Critical sections too small
  – Critical sections use wrong locks
  – Deadlocks

• Requires synchronization
  – Locks for mutual exclusion (common, various flavors)
  – Condition variables for signaling others (less common)

• Guidelines for correct use help avoid common pitfalls

• Not clear shared-memory is worth the pain
  – But other models (e.g., message passing) not a panacea