

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

```
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

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.

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*

- 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: **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

- 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?

```
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”

```
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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 - Condition variables

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

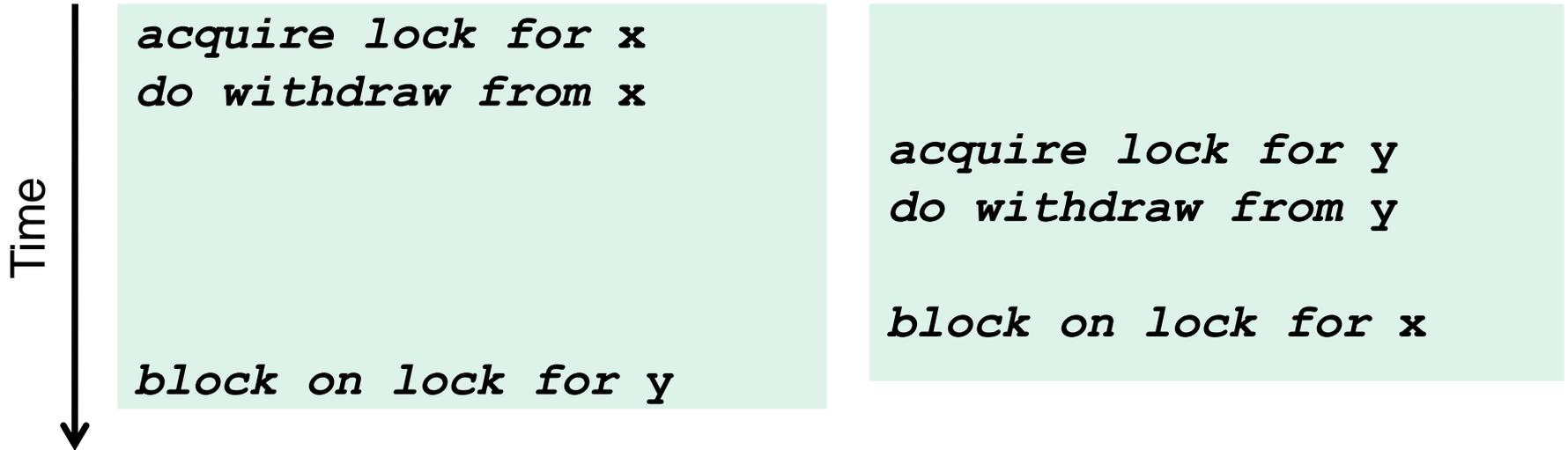
- Need to investigate when this may be a problem

The Deadlock

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

Thread 1: **x.transferTo(1, y)**

Thread 2: **y.transferTo(1, x)**



Deadlock, in general

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

- For $i=1, \dots, n-1$, **T_i** is waiting for a resource held by **T(i+1)**
- **T_n** 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);
                }
            }
    }
}
```

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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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”

$0 \leq \text{writers} \leq 1$
 $0 \leq \text{readers}$
 $\text{writers} * \text{readers} == 0$

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

Outline

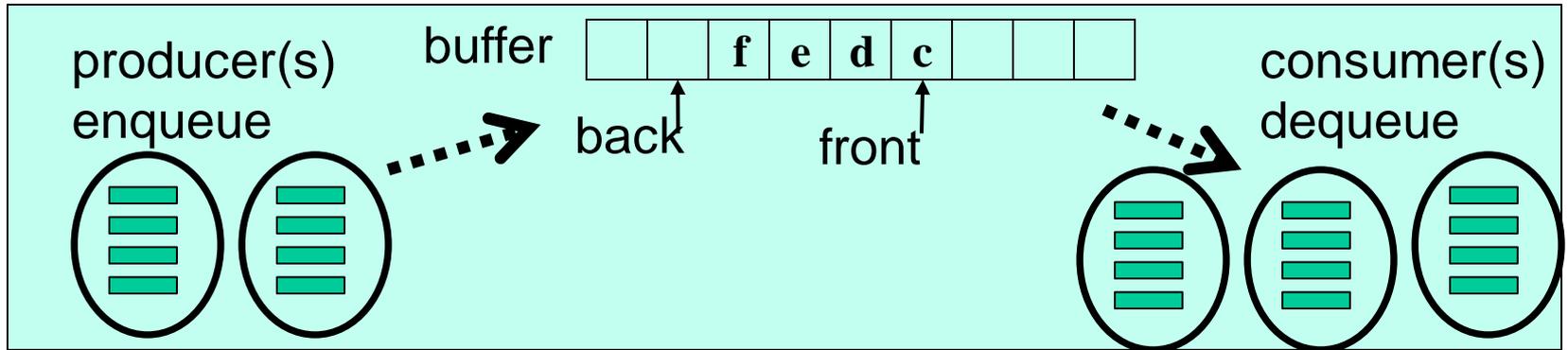
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 - **Condition variables**

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

Code, attempt 1

```
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)

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

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
    }
}
```

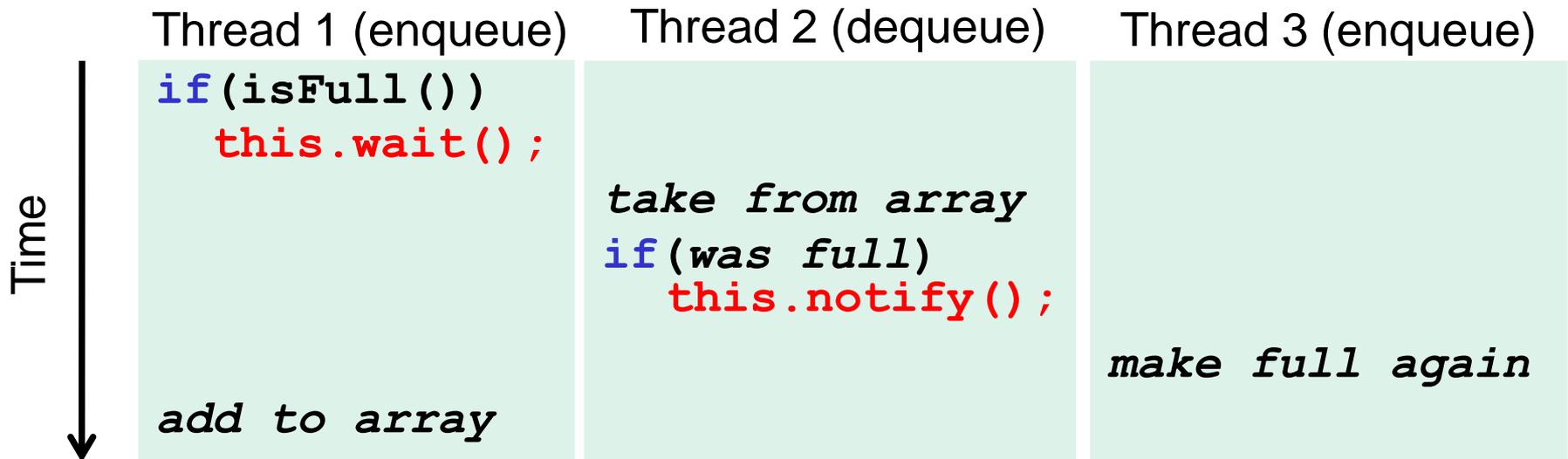
Key ideas

- 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

```
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!



Bug fix #1

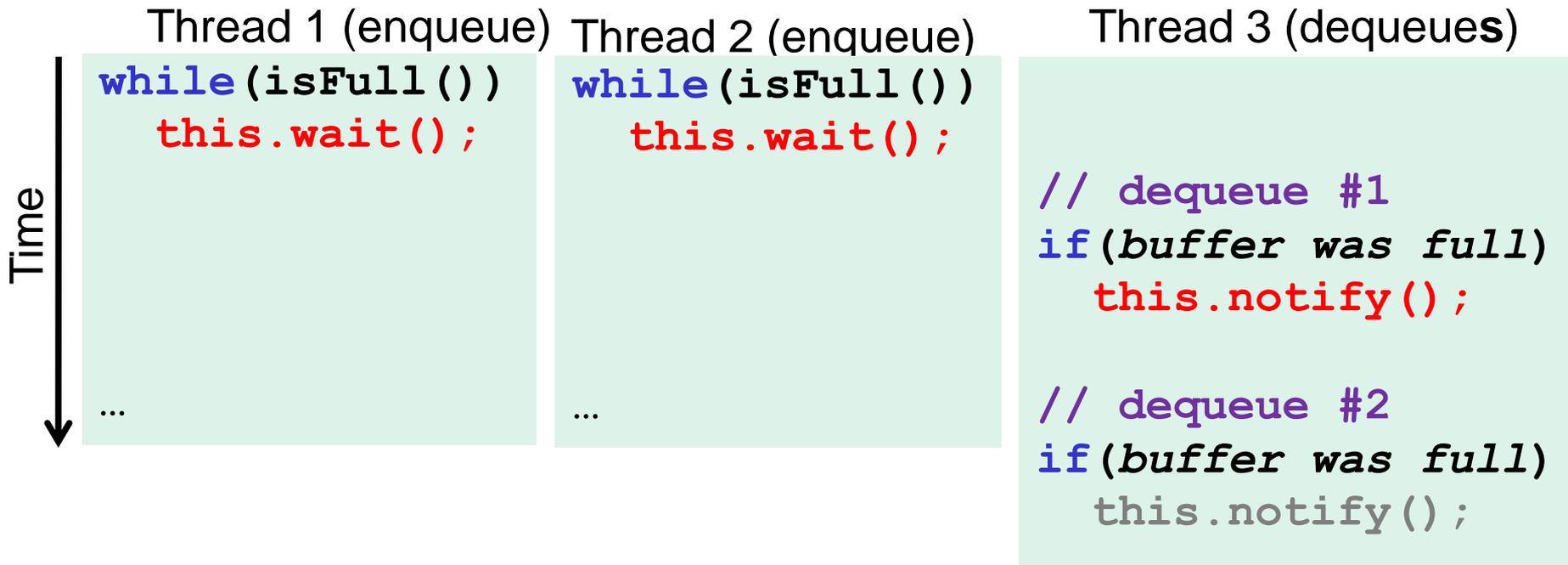
```
synchronized void enqueue (E elt) {  
    while (isFull ())  
        this.wait ();  
    ...  
}  
synchronized E dequeue () {  
    while (isEmpty ())  
        this.wait ();  
    ...  
}
```

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!



Bug fix #2

```
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 enqueueers 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