



## CSE 332: Data Abstractions

### Lecture 23: Data Races and Memory Reordering Deadlock Readers/Writer Locks Condition Variables

Ruth Anderson

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# *Announcements*

- **Homework 7** – due Friday March 8<sup>th</sup> at the BEGINNING of lecture!
- **Project 3** – the last programming project!
  - ALL Code - Tues March 12, 2011 11PM - (65% of overall grade):
  - Writeup - Thursday March 14, 2011, 11PM - (25% of overall grade)

# 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*...

will fail if  $b < a$

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# 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)

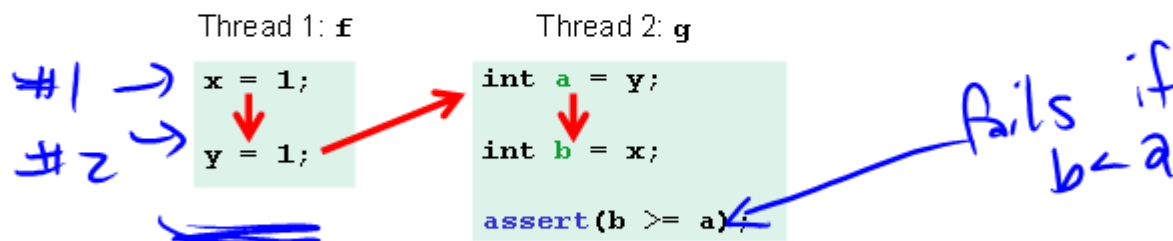
- Proof #2: If  $\neg (b \geq a)$ , then  $a == 1$  and  $b == 0$ .

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.



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# 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:  $x=17; y=x;$

$y=x$

3/06/2013

7

## *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);  
    }  
}
```

3/06/2013

9

## 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);  
    }  
}
```

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10

## Code that is wrong

- Here is a more realistic example of code that is wrong
  - No *guarantee* Thread 2 will ever stop (there's 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()

# 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

# 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);
    }
}
```

Potential problems?

Thread 1  
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x.transferTo(5, y)  
grab lock y

Thread 13  
y.transferTo(7, x)

✓

## 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

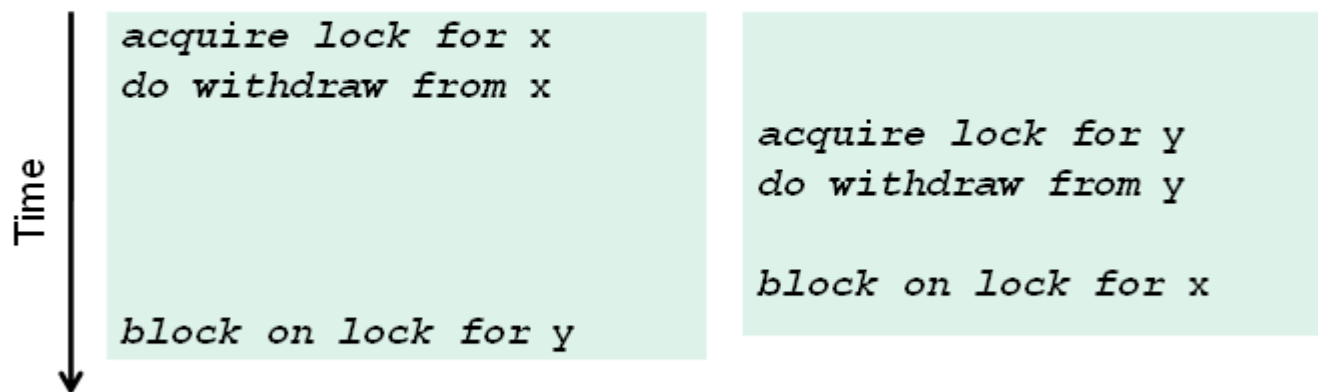
- Need to investigate when this may be a problem

# The Deadlock

Suppose  $x$  and  $y$  are static fields holding accounts

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

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



## *Ex: 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**



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16



## *Deadlock, in general*

A deadlock occurs when there are threads **T<sub>1</sub>**, ..., **T<sub>n</sub>** such that:

- For  $i=1, \dots, n-1$ , **T<sub>i</sub>** is waiting for a resource held by **T<sub>(i+1)</sub>**
- **T<sub>n</sub>** is waiting for a resource held by **T<sub>1</sub>**

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 here, 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

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18

## Ordering locks

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

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Thread 1  
 Act 1. transferTo(5, Act 2)  
 grab Act 1 lock first  
 then grab Act 2 lock

Thread 2  
 Act 2. transferTo(7, Act 1)  
 try to grab Act 1 lock  
 the Act 2 lock

## Another example

From the Java standard library

```
class StringBuffer {
    private int count; // "actual" size of string
    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"
    }
}
```

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2. append(b)  
b.getChar

b.append(a)  
a.getChar

## *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”

# 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

## *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
  - Won't allow simultaneous reads, even though it's ok conceptually
- 

But suppose:

- There are many simultaneous `lookup` operations
- `insert` operations are very rare
- It'd be nice to support multiple reads; we'd do lots of waiting otherwise

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”

$$\begin{array}{l} 0 \leq \text{writers} \leq 1 \\ 0 \leq \text{readers} \\ \text{writers} * \text{readers} == 0 \end{array}$$

## 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();  
    }  
}
```

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27

## 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*
    - That is, it could wait indefinitely because of continuous stream of read requests
- 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

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28

## *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

Done:

- Programming with locks and critical sections
- Key guidelines and trade-offs

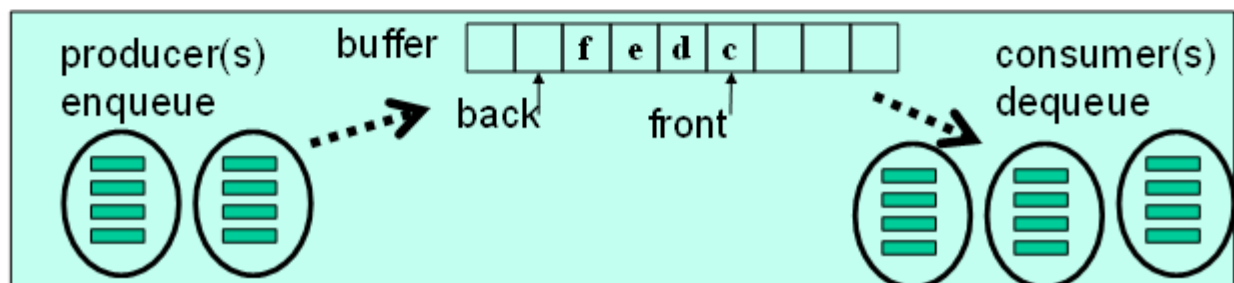
Now: The other basics an informed programmer needs to know

- 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**

## Motivating Condition Variables: Producers and Consumers

Another means of allowing concurrent access is the *condition variable*; before we get into that though, let's look at a situation where we'd need one:

- Imagine we have several *producer* threads and several *consumer* threads
  - Producers do work, toss their results into a buffer
  - Consumers take results off of buffer as they come and process them
  - Ex: Multi-step computation

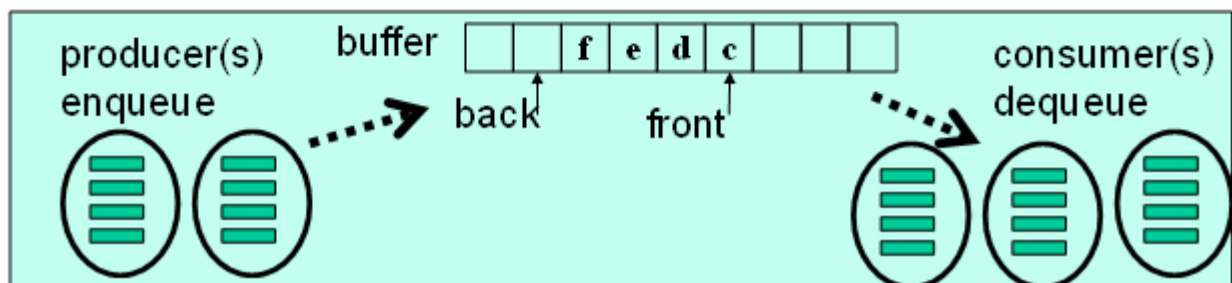


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31

## *Motivating Condition Variables: Producers and Consumers*

- Cooking analogy: Team one peels potatoes, team two takes those and slices them up
  - When a member of team one finishes peeling, they toss the potato into a tub
  - Members of team two pull potatoes out of the tub and dice them up

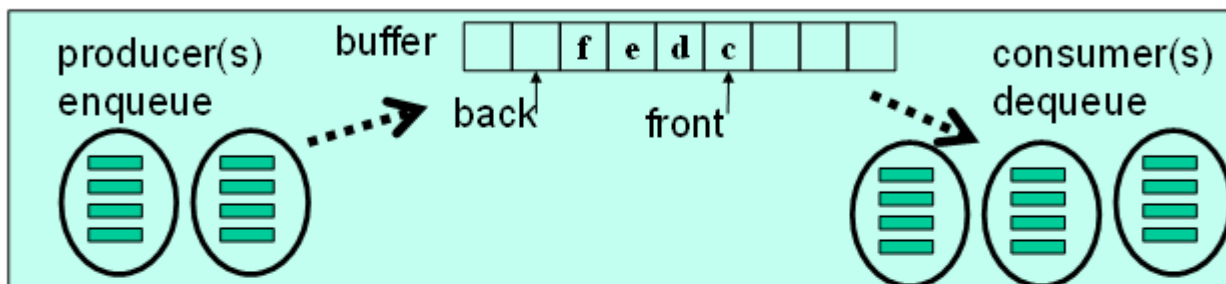


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32

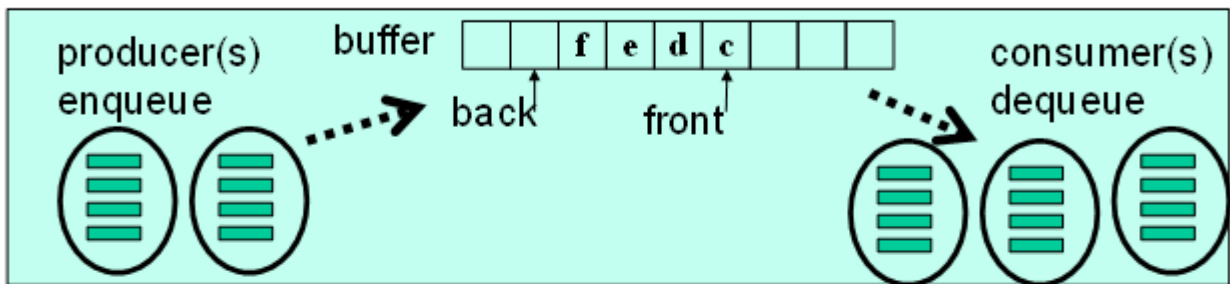


## Motivating Condition Variables: Producers and Consumers



- If the buffer is empty, consumers have to wait for producers to produce more data
- If buffer gets full, producers have to wait for consumers to consume some data and clear space
- We'll need to synchronize access; why?
  - Data race; simultaneous read/write or write/write to back/front

## 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 ...
    }
}
```

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35

## First attempt

```
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 ...
    }
}
```

- What to do for ??? One approach; if buffer is full on enqueue, or empty on dequeue, throw an exception
  - **Not** what we want here; w/ multiple threads taking & giving, these will be common occurrences – should not handle like errors
  - Common, and only temporary; will only be empty/full briefly
  - Instead, we want threads to be pause until it can proceed

## 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
  - Thread suspended until then; in meantime, other threads run
  - While *waiting*, lock is released; will be re-acquired later by one *notified* thread
  - Upon being notified, thread just drops in to see what condition it's condition is in
  - Team two members work on something else until they're told more potatoes are ready
  - Less contention for lock, and time waiting spent more efficiently

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## Condition Variables

- Like locks & threads, not something you can implement on your own
  - Language or library gives it to you
- An ADT that supports this: **condition variable**
  - Informs waiting thread(s) when the *condition* that causes it/them to wait has *varied*
- Terminology not completely standard; will mostly stick with Java

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## 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  
    }  
}
```

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40



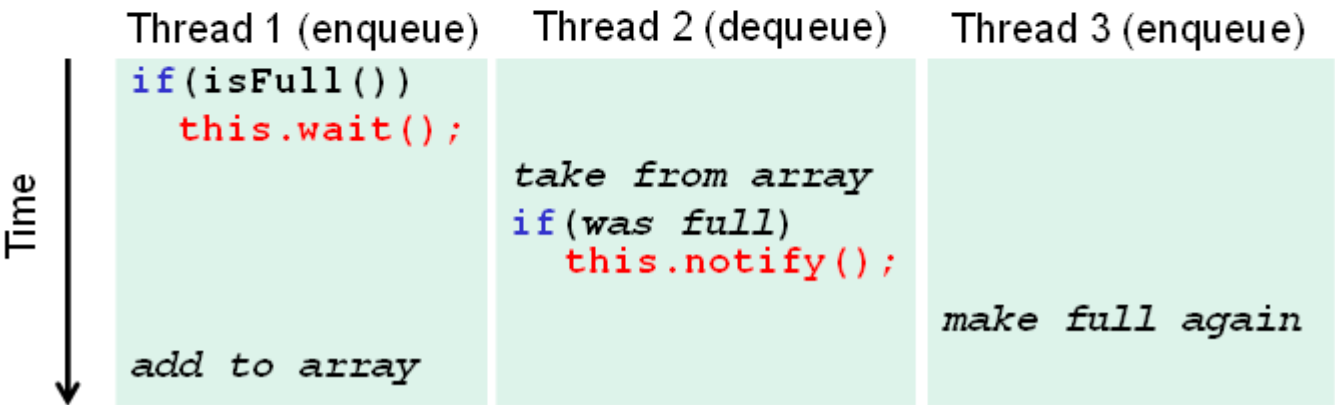
## Key ideas

- 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

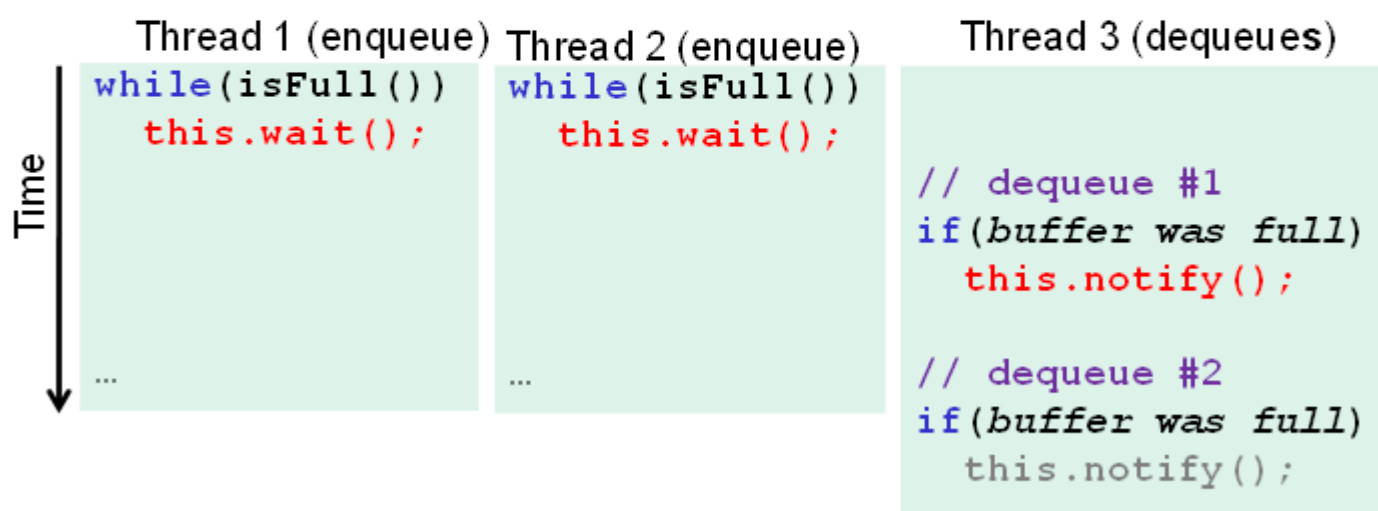
```
synchronized void enqueue(E elt) {  
    while(isFull())  
        this.wait();  
    ...  
}  
synchronized E dequeue() {  
    while(isEmpty())  
        this.wait();  
    ...  
}
```

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

- If condition still not met, go back to waiting
- 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!
  - Works for the most part, but what if 2 are waiting to enqueue, and two quick dequeues occur before either gets to go?
  - We'd only notify once; other thread would wait forever



## 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...

3/06/2013

45

## *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