CSE 332: Data Abstractions

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

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Announcements

- **Homework 7** – due Friday May 31

- **Project 3** – the last programming project!
  - ALL Code - Tues June 4, 2013 11PM
  - Experiments & Writeup - Thurs June 6, 2013, 11PM

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*…

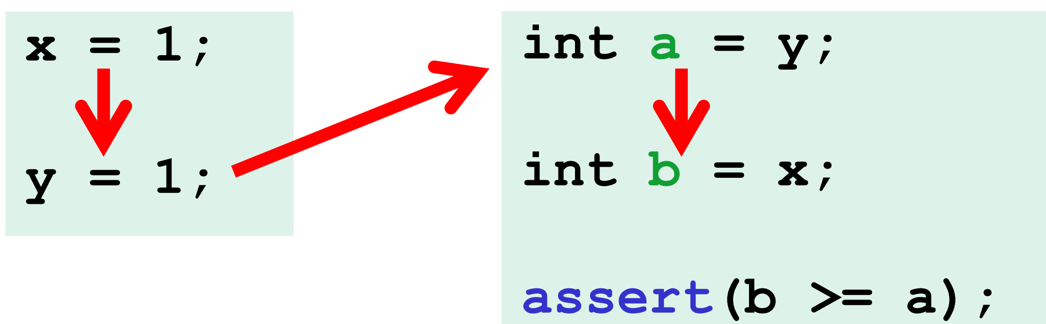
Interleavings

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>=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`**

Thread 2: **`g`**



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 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()`

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- 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?

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

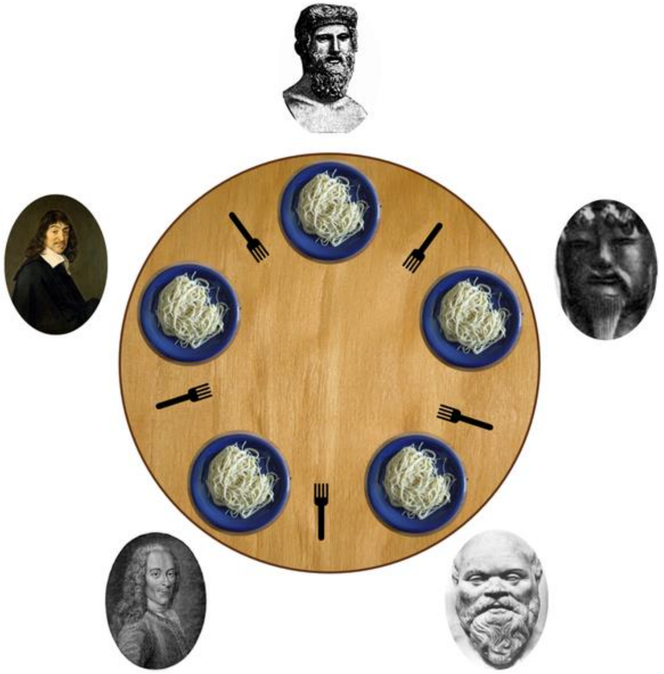
The Deadlock

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

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`	

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***



Deadlock, in general

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 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

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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  - 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

$0 \le$ writers ≤ 1
$0 \le$ readers
writers*readers==0

- **`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"

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*
    - 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

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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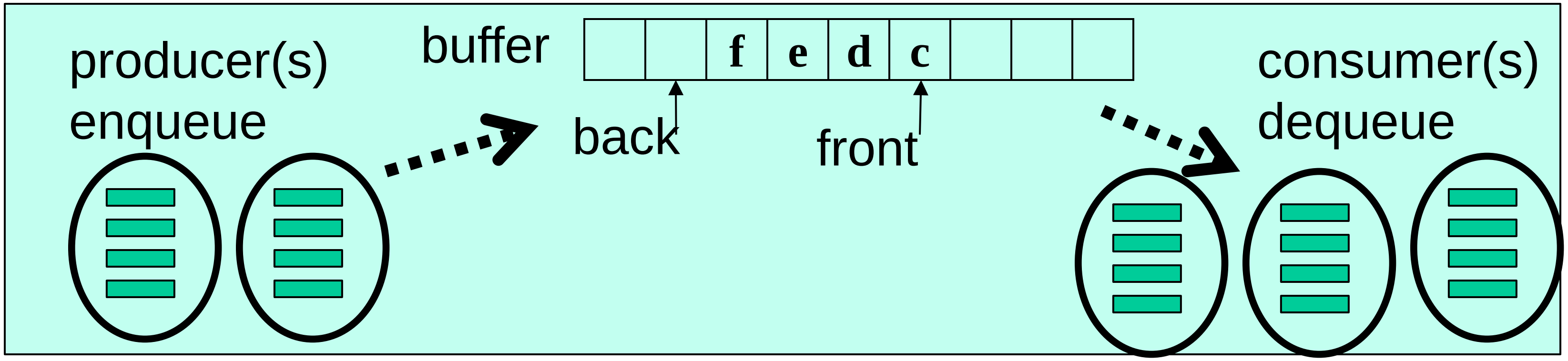
Motivating Condition Variables: Producers and Consumers

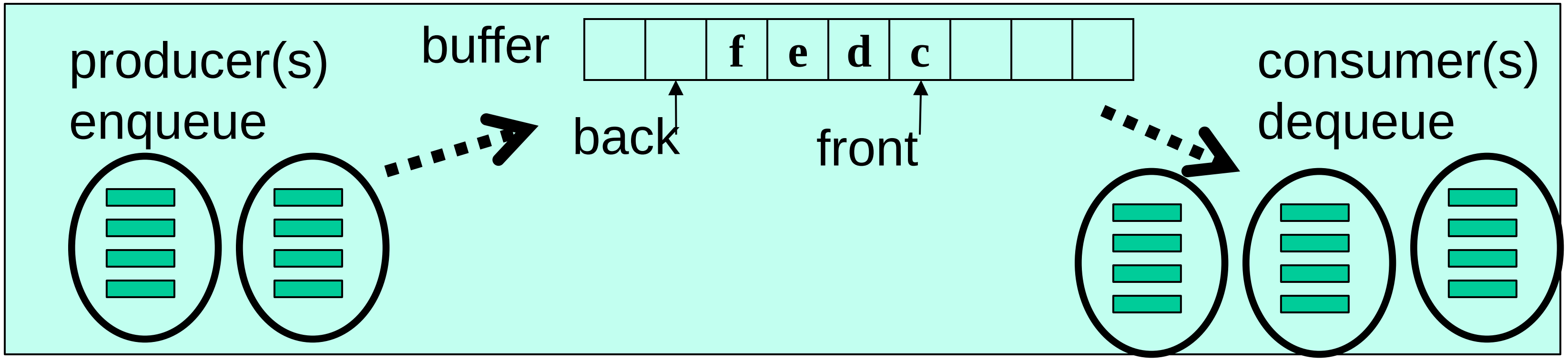
Another means of allowing concurrent access is the *condition variable*; before we get into that though, lets look at a situation where we'd need one:

- 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

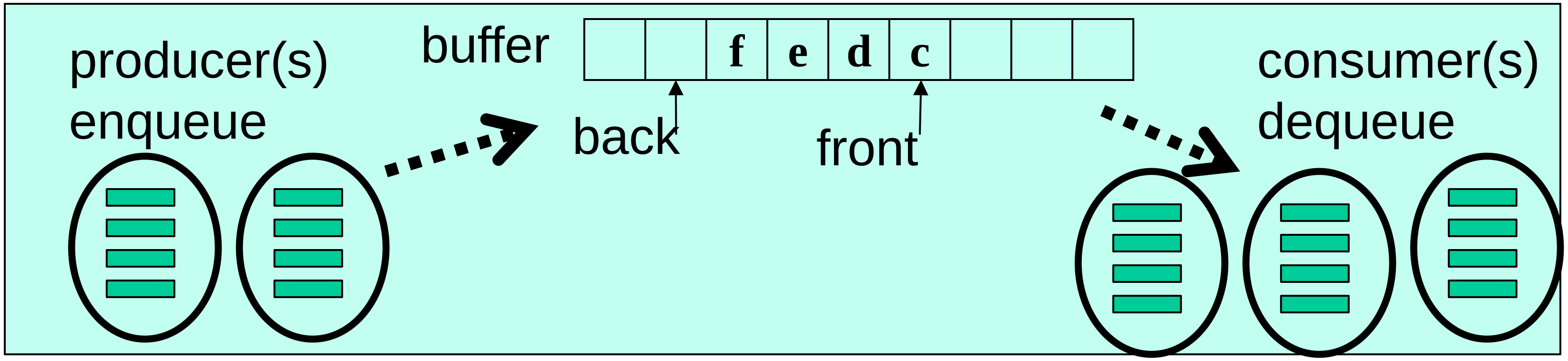


Motivating Condition Variables: Producers and Consumers

- 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

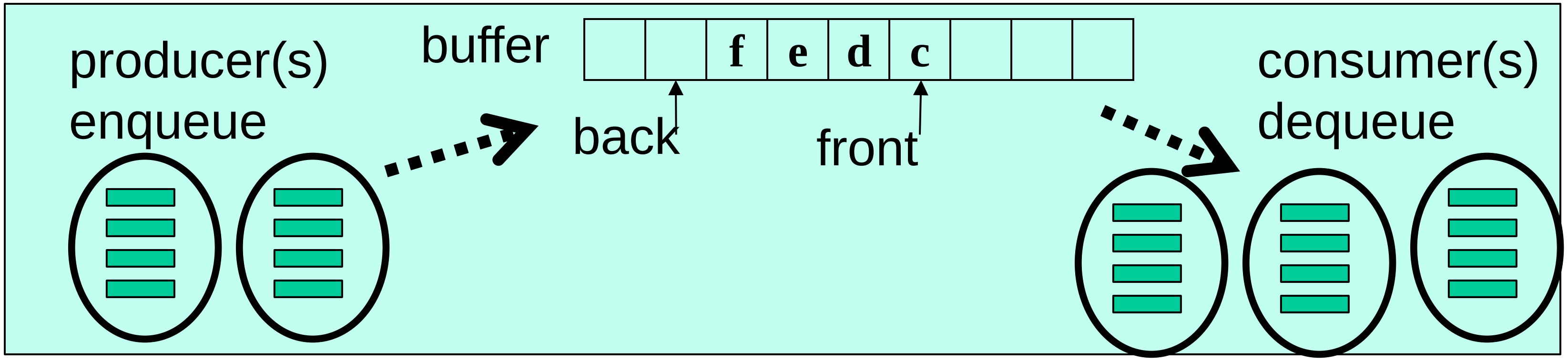


Motivating Condition Variables: Producers and Consumers



- 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 …
  }
}
```

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

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

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!

Time	Thread 1 (enqueue)	Thread 2 (dequeue)	Thread 3 (enqueue)
↓	`if(isFull())`		
	`this.wait();`		
		`take from array`	
		`if(was full)`	
		`this.notify();`	
			`make full again`
	`add to array`		

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

Time

Thread 1 (enqueue)

```
while(isFull())
  this.wait();

…
```

Thread 2 (enqueue)

```
while(isFull())
  this.wait();

…
```

Thread 3 (dequeue**s**)

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

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

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 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