COMP 322: Fundamentals of Parallel Programming

Lecture 26: Java Threads, Locks

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Introduction to Java Threads and the java.lang.Thread class

- Execution of a Java program begins with an instance of Thread created by the Java Virtual Machine (JVM) that executes the program's main() method.
- Parallelism can be introduced by creating additional instances of class Thread that execute as parallel threads.

```
public class Thread extends Object implements Runnable {
  Thread() { ... } // Creates a new Thread
  Thread(Runnable r) { ... } // Creates a new Thread with Runnable object r
  void run() { ... } // Code to be executed by thre
   // Case 1: If this thread was
   //          then that object's run method
   // Case 2: If this class is subclassed, t
   //          in the subclass is called
  void start() { ... } // Causes this thread to
  void join() { ... } // Wait for this thread to die
  void join(long m) // Wait at most m milliseconds for thread to die
  static Thread currentThread() // Returns currently executing thread
  . . .
}
```

A lambda can be passed as a Runnable

start() and join() methods

- A Thread instance starts executing when its start() method is invoked
  - start() can be invoked at most once per Thread instance
  - As with async, the parent thread can immediately move to the next statement after invoking t.start()
- A t.join() call forces the invoking thread to wait till thread t completes.
  - Lower-level primitive than finish since it only waits for a single thread rather than a collection of threads
  - No restriction on which thread performs a join on which thread, so it is possible to create a deadlock cycle using join() even when there are no data races

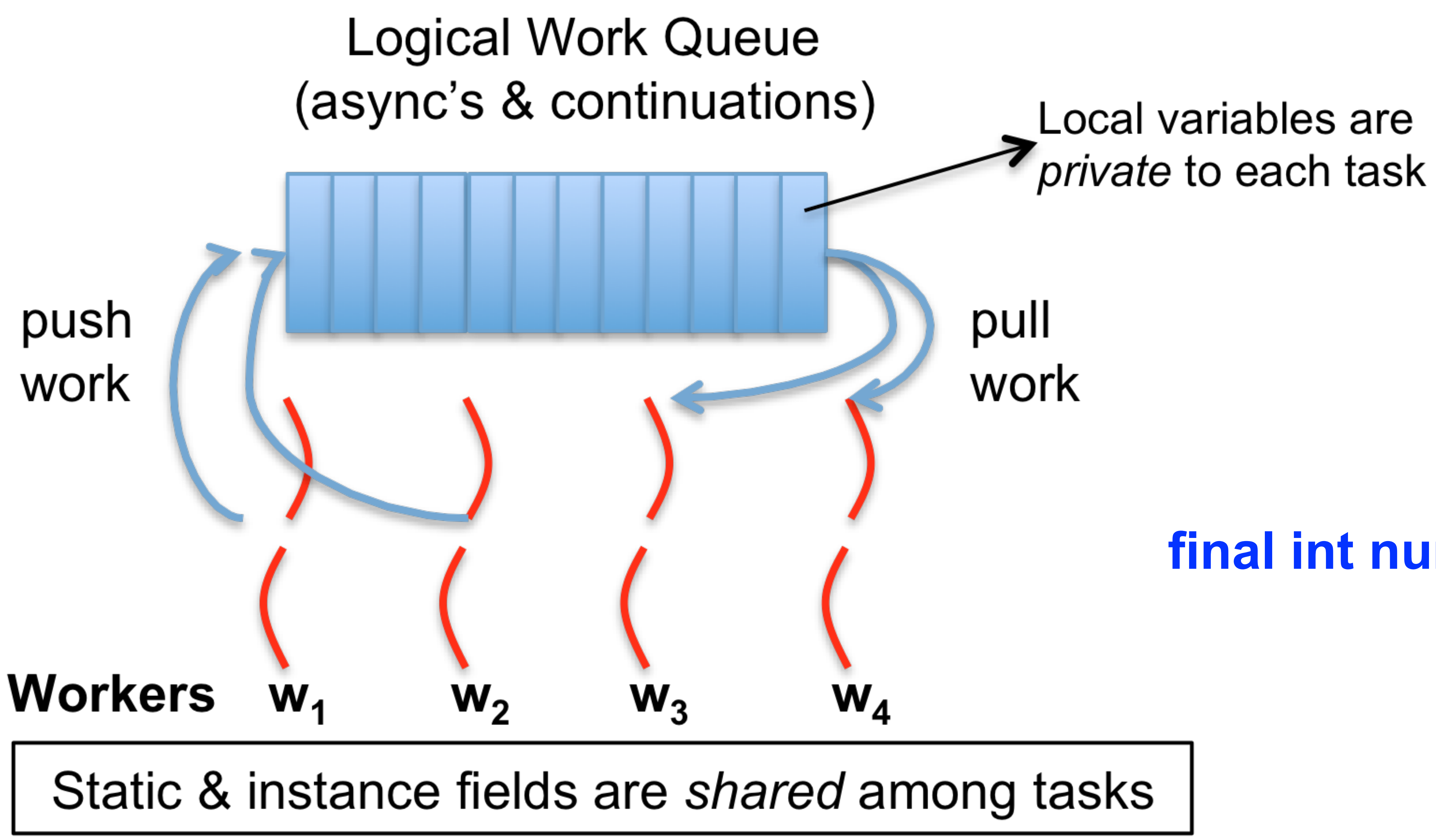
Two-way Parallel Array Sum using Java Threads

```
// Start of main thread
sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
Thread t1 = new Thread(() -> {
    // Child task computes sum of lower half of array
    for(int i=0; i < X.length/2; i++) sum1 += X[i];
  });
t1.start();
// Parent task computes sum of upper half of array
for(int i=X.length/2; i < X.length; i++) sum2 += X[i];
// Parent task waits for child task to complete (join)
t1.join();
return sum1 + sum2;
```

Compare with Two-way Parallel Array Sum using HJ-Lib's finish & async API's

```
// Start of Task T0 (main program)
sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
finish(() -> {
  async(() -> {
    // Child task computes sum of lower half of array
    for(int i=0; i < X.length/2; i++) sum1 += X[i];
  });
  // Parent task computes sum of upper half of array
  for(int i=X.length/2; i < X.length; i++) sum2 += X[i];
});
// Parent task waits for child task to complete (join)
return sum1 + sum2;
```

HJlib runtime uses Java threads as workers



final int numThreads = numWorkerThreads()

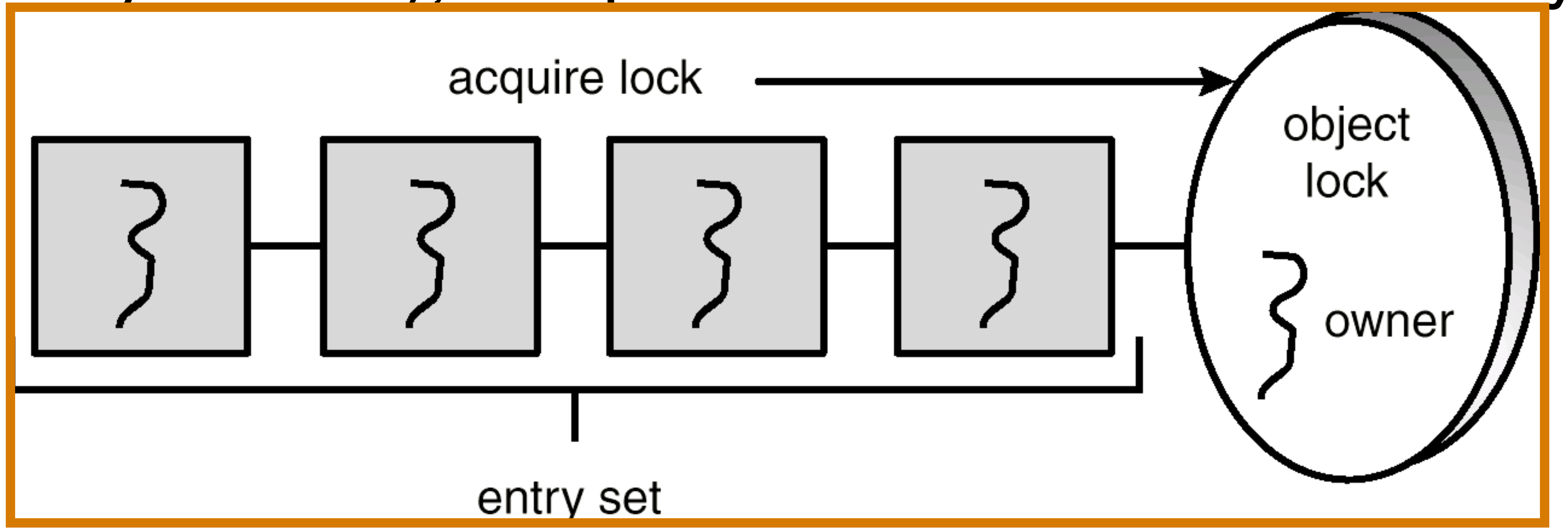
- HJlib runtime creates a small number of worker threads in a *thread pool*, typically one per core
- Workers push async's/continuations into a logical work queue
  - when an async operation is performed
  - when an end-finish operation is reached
- Workers pull task/continuation work item when they are idle

Locking guarantees in Java

- It is preferable to use java.util.concurrent.atomic or HJlib isolated constructs, since they cannot deadlock
- Locks are needed for more general cases. Basic idea is for JVM to implement synchronized(a) <stmt> as follows:
  1. Acquire lock for object a
  2. Execute <stmt>
  3. Release lock for object a
- The responsibility for ensuring that the choice of locks correctly implements the semantics of isolation lies with the programmer.
- The main guarantee provided by locks is that only one thread can hold a given lock at a time, and the thread is blocked when acquiring a lock if the lock is unavailable.

Implementation of Java synchronized statements/methods

- Every object has an associated lock
- “synchronized” is translated to matching monitorenter and monitorexit bytecode instructions for the Java virtual machine
  - monitorenter requests “ownership” of the object’s lock
  - monitorexit releases “ownership” of the object’s lock
- If a thread performing monitorenter does not gain ownership of the lock (because another thread already owns it), it is placed in an unordered “entry set” for the object’s lock



Locks

- Use of monitor synchronization is just fine for most applications, but it has some shortcomings
  - Single wait-set per lock
  - No way to interrupt or time-out when waiting for a lock
  - Locking must be block-structured
    - Inconvenient to acquire a variable number of locks at once
    - Advanced techniques, such as hand-over-hand locking, are not possible
- Lock objects address these limitations
  - But harder to use: Need **`finally`** block to ensure release
  - So if you don't need them, stick with **`synchronized`**

Example of hand-over-hand locking:

- L1.lock() … L2.lock() … L1.unlock() … L3.lock() … L2.unlock() ….

java.util.concurrent.locks.Lock interface

```
interface Lock {
    // key methods
    void lock(); // acquire lock
    void unlock(); // release lock
    boolean tryLock(); // Either acquire lock (returns true), or return false if lock is not obtained.
                       // A call to tryLock() never blocks!

    Condition newCondition();  // associate a new condition
}
```

java.util.concurrent.locks.Lock interface is implemented by java.util.concurrent.locks.ReentrantLock class

Simple ReentrantLock() example

- Used extensively within **`java.util.concurrent`**

```
final Lock lock = new ReentrantLock();
 ...
 lock.lock();
 try {
   // perform operations protected by lock
 }
 catch(Exception ex) {
   // restore invariants & rethrow
 }
 finally {
   lock.unlock();
 }
```

- **Must manually ensure lock is released**

==> Importance of including call to unlock() in finally clause!

What if you want to wait for shared state to satisfy a desired property? (Bounded Buffer Example)

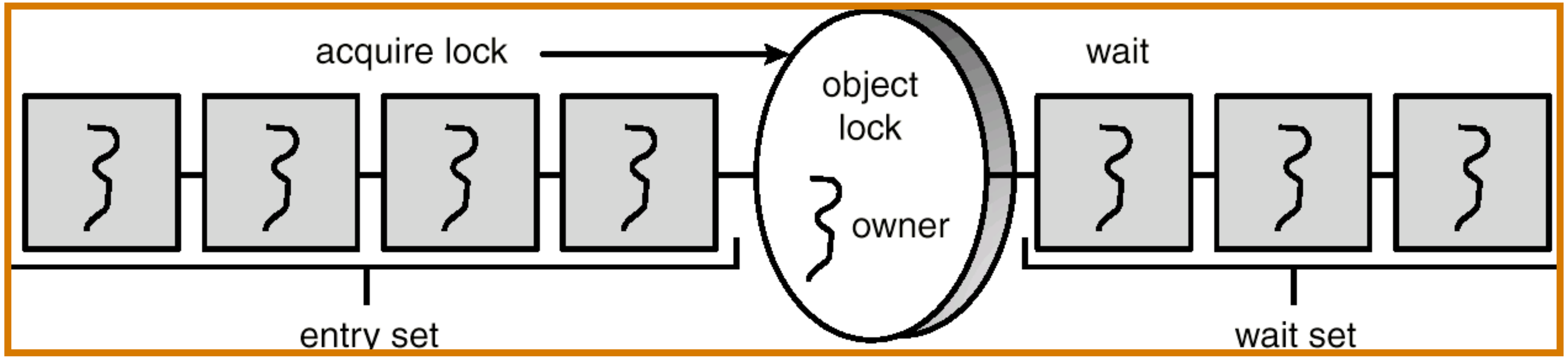
```
public synchronized void insert(Object item) { // producer
  // TODO: wait till count < BUFFER SIZE
  ++count;
  buffer[in] = item;
  in = (in + 1) % BUFFER SIZE;
  // TODO: notify consumers that an insert has been performed
}

public synchronized Object remove() { // consumer
  Object item;
   // TODO: wait till count > 0
  --count;
  item = buffer[out];
  out = (out + 1) % BUFFER SIZE;
  // TODO: notify producers that a remove() has been performed
  return item;
}
```

The Java wait() Method

- A thread can perform a wait():
  1. the thread releases the object lock
  2. thread state is set to blocked
  3. thread is placed in the wait set
- Causes thread to wait until another thread invokes the notify() method or the notifyAll() method for this object.
- Should always be used in a loop

Entry and Wait Sets



The notify() Method

When a thread calls notify(), the following occurs:

1. selects an arbitrary thread T from the wait set
2. moves T to the entry set
3. sets T to Runnable

T can now compete for the object's lock again

Multiple Notifications

- notify() selects an arbitrary thread from the wait set.
  - This may not be the thread that you want to be selected.
  - Java does not allow you to specify the thread to be selected
- notifyAll() removes ALL threads from the wait set and places them in the entry set. This allows the threads to decide among themselves who should proceed next.
- notifyAll() is a conservative strategy that works best when multiple threads may be in the wait set

What if you want to wait for shared state to satisfy a desired property? (Bounded Buffer Example)

```
public synchronized void insert(Object item) { // producer
  while(count == buffer.length()) wait();
  ++count;
  buffer[in] = item;
  in = (in + 1) % BUFFER SIZE;
  notify();
}

public synchronized Object remove() { // consumer
  Object item;
  while(count == 0) wait();
  --count;
  item = buffer[out];
  out = (out + 1) % BUFFER SIZE;
  notify();
  return item;
}
```

java.util.concurrent.locks.condition interface

- Can be allocated by calling ReentrantLock.newCondition()
- Supports multiple condition variables per lock
- Methods supported by an instance of condition
  - void await()   // NOTE: like wait() in synchronized statement
    - Causes current thread to wait until it is signaled or interrupted
    - Variants available with support for interruption and timeout
  - void signal() // NOTE: like notify() in synchronized statement
    - Wakes up one thread waiting on this condition
  - void signalAll() // NOTE: like notifyAll() in synchronized statement
    - Wakes up all threads waiting on this condition
- For additional details see
  - http://download.oracle.com/javase/1.5.0/docs/api/java/util/concurrent/locks/Condition.html

BoundedBuffer Example using Two Conditions: full and empty

```
class BoundedBuffer {
  final Lock lock = new ReentrantLock();
  final Condition full  = lock.newCondition();
  final Condition empty = lock.newCondition();

  final Object[] items = new Object[100];
  int putptr, takeptr, count;

   . . .
```

BoundedBuffer Example using Two Conditions: full and empty (contd)

```
public void put(Object x) throws InterruptedException
 {
   lock.lock();
   try {
     while (count == items.length) full.await();
     items[putptr] = x;
     if (++putptr == items.length) putptr = 0;
     ++count;
     empty.signal();
   } finally {
       lock.unlock();
   }
 }
```

BoundedBuffer Example using Two Conditions: full and empty (contd)

```
public Object take() throws InterruptedException
{
  lock.lock();
  try {
    while (count == 0) empty.await();
    Object x = items[takeptr];
    if (++takeptr == items.length) takeptr = 0;
    --count;
    full.signal();
    return x;
  } finally {
    lock.unlock();
  }
}
```