COMP 322: Fundamentals of Parallel Programming

Lecture 27: 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.

```
1  public class Thread extends Object implements Runnable {
2    Thread() { ... } // Creates a new Thread
3    Thread(Runnable r) { ... } // Creates a new Thread with Runnable object r
4    void  run() { ... } //
5     // Case 1: If this thread was
6     //          then that object's run metho
7     // Case 2: If this class is subclassed, t
8     //          in the subclass is called
9    void start() { ... } // Causes this thread to
10   void join() { ... } // Wait for this thread to die
11   void  join(long m) // Wait at most m milliseconds for thread to die
12   static Thread currentThread() // Returns currently executing thread
13   . . .
14 }
```

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

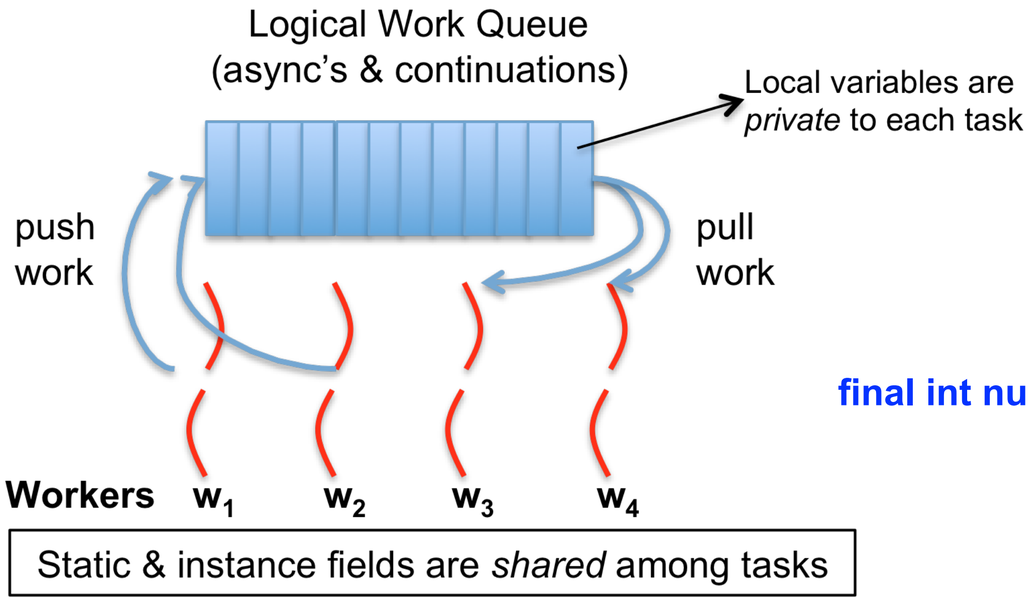
Two-way Parallel Array Sum using Java Threads

```
1.  // Start of main thread
2.  sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
3.  Thread t1 = new Thread(() -> {
4.      // Child task computes sum of lower half of array
5.      for(int i=0; i < X.length/2; i++) sum1 += X[i];
6.    });
7.  t1.start();
8.  // Parent task computes sum of upper half of array
9.  for(int i=X.length/2; i < X.length; i++) sum2 += X[i];
10. // Parent task waits for child task to complete (join)
11. t1.join();
12. return sum1 + sum2;
```


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

```
1.  // Start of Task T0 (main program)
2.  sum1 = 0; sum2 = 0; // sum1 & sum2 are static fields
3.  finish(() -> {
4.    async(() -> {
5.      // Child task computes sum of lower half of array
6.      for(int i=0; i < X.length/2; i++) sum1 += X[i];
7.    });
8.    // Parent task computes sum of upper half of array
9.    for(int i=X.length/2; i < X.length; i++) sum2 += X[i];
10. });
11. // Parent task waits for child task to complete (join)
12. return sum1 + sum2;
```


HJlib runtime uses Java threads as workers



final int numThreads = numWorkerThreads()

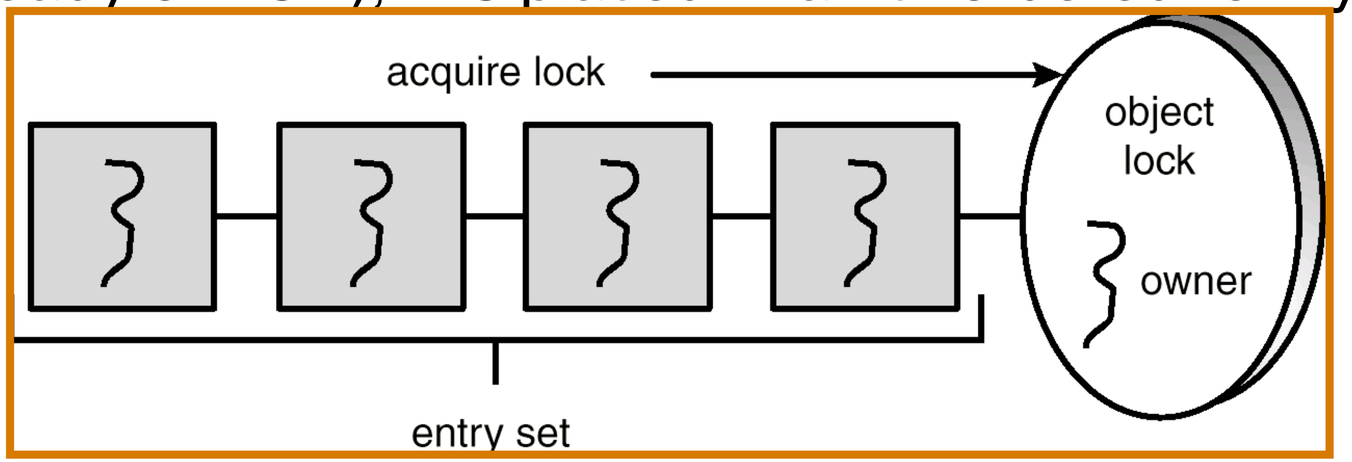
- HJlib runtime creates a small number of worker threads in a *thread pool*, typically one per core
- Workers push async's/continuations into a logical work queue
  - when an async operation is performed
  - when an end-finish operation is reached
- Workers pull task/continuation work item when they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

```
1. interface Lock {
2.     // key methods
3.     void lock(); // acquire lock
4.     void unlock(); // release lock
5.     boolean tryLock(); // Either acquire lock (returns true), or return false if lock is not obtained.
6.                                 // A call to tryLock() never blocks!
7.
8.     Condition newCondition();  // associate a new condition
9. }
```

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)

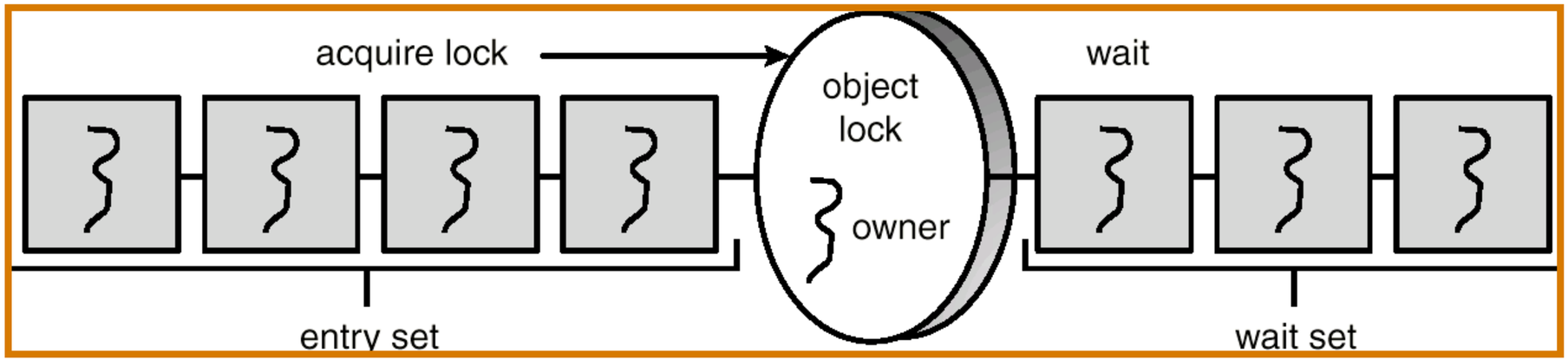
```
1.  public synchronized void insert(Object item) { // producer
2.    // TODO: wait till count < BUFFER SIZE
3.    ++count;
4.    buffer[in] = item;
5.    in = (in + 1) % BUFFER SIZE;
6.    // TODO: notify consumers that an insert has been performed
7.  }

9.  public synchronized Object remove() { // consumer
10.  Object item;
11.   // TODO: wait till count > 0
12.  --count;
13.  item = buffer[out];
14.  out = (out + 1) % BUFFER SIZE;
15.  // TODO: notify producers that a remove() has been performed
16.  return item;
17.}
```


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)

```
1.  public synchronized void insert(Object item) { // producer
2.    while(count == buffer.length()) wait();
3.    ++count;
4.    buffer[in] = item;
5.    in = (in + 1) % BUFFER SIZE;
6.    notify();
7.  }

9.  public synchronized Object remove() { // consumer
10.  Object item;
11.  while(count == 0) wait();
12.  --count;
13.  item = buffer[out];
14.  out = (out + 1) % BUFFER SIZE;
15.  notify();
16.  return item;
17.}
```


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

```
1. class BoundedBuffer {
2.   final Lock lock = new ReentrantLock();
3.   final Condition full  = lock.newCondition();
4.   final Condition empty = lock.newCondition();
5.
6.   final Object[] items = new Object[100];
7.   int putptr, takeptr, count;
8.
9.    . . .
```


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

```
1.  public void put(Object x) throws InterruptedException
2.   {
3.     lock.lock();
4.     try {
5.       while (count == items.length) full.await();
6.       items[putptr] = x;
7.       if (++putptr == items.length) putptr = 0;
8.       ++count;
9.       empty.signal();
10.     } finally {
11.       lock.unlock();
12.     }
13.   }
```

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

```
1.  public Object take() throws InterruptedException
2.  {
3.    lock.lock();
4.    try {
5.      while (count == 0) empty.await();
6.      Object x = items[takeptr];
7.      if (++takeptr == items.length) takeptr = 0;
8.      --count;
9.      full.signal();
10.       return x;
11.   } finally {
12.     lock.unlock();
13.   }
14. }
```