Lecture 24: Shared Memory Concurrency/Parallelism

CSC 131
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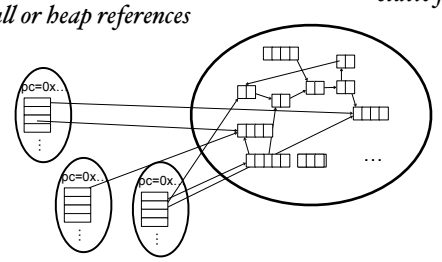
Shared Memory

Threads, each with own unshared call stack and current statement (pc for "program counter") local variables are numbers/null or heap references

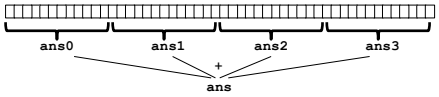
Heap for all objects and static fields



Parallel Programming in Java

- Creating a thread:
  1. Define a class C extending Thread
     - Override `public void run()` method
  2. Create object of class C
  3. Call that thread's start method
     - Creates new thread and starts executing run method.
     - Direct call of run won't work, as just be a normal method call
- *Alternatively, define class implementing Runnable, create thread w/it as parameter, and send start message*

Parallelism Idea



- Example: Sum elements of an array
  - Use 4 threads, which each sum 1/4 of the array
- Steps:
  - Create 4 thread objects, assigning each their portion of the work
  - Call start() on each thread object to actually run it
  - Wait for threads to finish
  - Add together their 4 answers for the final result

First Attempt

```
class SumThread extends Thread {
  int lo, int hi, int[] arr;//fields to know what to do
  int ans = 0; // for communicating result
  SumThread(int[] a, int l, int h) { … }
  public void run(){ … }
}

int sum(int[] arr){
  int len = arr.length;
  int ans = 0;
  SumThread[] ts = new SumThread[4];
  for(int i=0; i < 4; i++){// do parallel computations
    ts[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
    ts[i].start(); // use start not run
  }
  for(int i=0; i < 4; i++) // combine results
    ans += ts[i].ans;
  return ans;
}
```

What's wrong?

Correct Version

```
class SumThread extends Thread {
  int lo, int hi, int[] arr;//fields to know what to do
  int ans = 0; // for communicating result
  SumThread(int[] a, int l, int h) { … }
  public void run(){ … }
}

int sum(int[] arr){
  int len = arr.length;
  int ans = 0;
  SumThread[] ts = new SumThread[4];
  for(int i=0; i < 4; i++){// do parallel computations
    ts[i] = new SumThread(arr,i*len/4,(i+1)*len/4);
    ts[i].start(); // start not run
  }
  for(int i=0; i < 4; i++) // combine results
    ts[i].join(); // wait for helper to finish!
    ans += ts[i].ans;
  return ans;
}
```

See program ParallelSum

Thread Class Methods

- void start( ), which calls void run( )
- void join( ) -- blocks until receiver thread done
- Style called fork/join parallelism
  - Code on previous slide generates error message as join can throw exception InterruptedException
- Some memory sharing: arr field
- Later learn how to protect using synchronized.

Actually not so great.

- If do timing, it's slower w/ small arrays than sequential!!
- Want code to be reusable and efficient as core count grows.
  - At minimum, make #threads a parameter.
- Want to effectively use processors available *now*
  - Not being used by other programs
  - Can change while your threads running

Problem

- Suppose 4 processors on computer
- Suppose have problem of size n
  - can solve w/3 processors each taking time t on n/3 elts.
- Suppose linear in size of problem.
  - Try to use 4 threads, but one processor busy playing music.
  - First 3 threads run, but 4th waits.
    - First 3 threads scheduled & take time (n/4)/(n/3)*t = 3/4 t
    - After 1st 3 finish, run 4th & takes another 3/4 t
    - Total time 1.5 * t , runs 50% slower than with 3 threads!!!

Other Possible Problems

- On some problems, different threads may take significantly different times to complete
- Apply f to all members of an array, where f applied to some elts takes a long time
- All slow elts may get assigned to same thread.
  - Certainly won't see n time speedup w/ n threads.
  - May be much worse! Load imbalance problem!

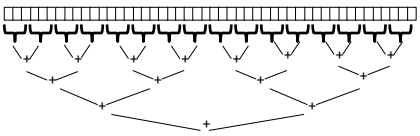
Toward a Solution

- To avoid having to wait too long for any one thread, instead create lots of threads
- Schedule threads as processors become available.
- If 1 thread very slow, many others will get scheduled on other processors while that one runs.
- Will work well if slow thread scheduled relatively early.

Naive Algorithm Not Work

- Suppose divide up work into threads which each handle 100 elts.
- Then will be n/100 threads.
  - Adding them up linear in size of array
  - If each thread handles only 1 sum then back to sequential algorithm.

Divide & Conquer



- Divide in half, w/ one thread per half.
  - Each half further subdivided w/ new threads, etc. until down to single elements
  - Depth is O(log n), which is optimal
  - Then total time w/numProc processors
    O(n/numProc + log n)

straight-line code cost in step 1

each layer is O(1) in parallel

In practice

- Creating all threads and communication swamps savings so
  - use sequential cutoff about 1000
  - Don't create two recursive threads
    - one new and reuse old.
    - Cuts number of threads in half.

EfficentDivideConquerParallelSum

Even Better

- Java threads too heavyweight -- space and time overhead.
- ForkJoin Framework solves problems
- Will be in Java 7, but early release in jsr166.jar.

To Use Library

- Create a ForkJoinPool
- Instead of subclass Thread, subclass RecursiveTask<V>
- Override compute, rather than run
- Return answer from compute rather than instance vble
- Call fork instead of start
- Call join that returns answer
- To optimize, call compute instead of fork (*rather than run*)
- See *ForkJoinFrameworkDivideConquerParallelSum*

Handling Concurrency in Java

See ATM example

Synchronized blocks

- Control access w/ synchronized blocks:
  - `synchronized(someObj){...}`
  - Must hold lock to access. Release when exit.
- Synchronized methods:
  - Implicitly use "this" as lock on method body

Shared Variables

- Variables read/written by more than one process are vulnerable to race conditions.
  - Even ++n is vulnerable, as not atomic
  - But there are "atomic" types like AtomicInteger
- If multiple threads access the same mutable state variable you have two options:
  - Make the state variable immutable
  - Use synchronization whenever accessing the state variable

Shared Variables

- Visibility of changes:
  - If one thread executes synchronized block, and then another thread enters a block with same lock, then current values of variables accessible by first are visible to second when acquires lock
  - Without synchronization, no guarantees!
    - May reorder, may be in cache or register or ...
- If synchronization not necessary, then label vble as volatile to force changes to be visible

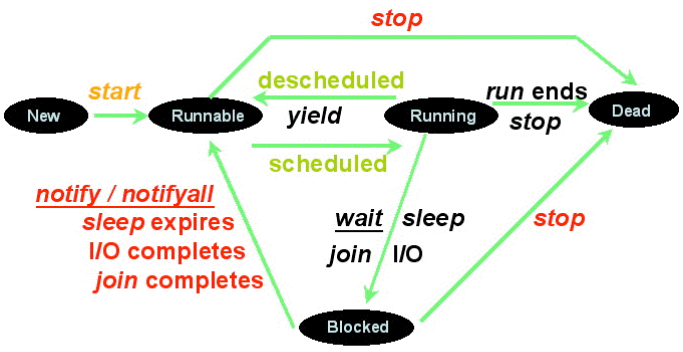
Conditional Waiting

- Every object has a wait set
- `wait()`: release lock & pause until another thread calls notify or notifyAll.
- `notify(), notifyAll()`: wake up waiting threads, which try to grab lock
  - *Can only be used in synchronized code*
  - *Notify wakes up single thread -- arbitrary choice*
  - *NotifyAll wakes up all waiting threads*
  - *Much better than busy-waiting (spin-locks)*

Thread States in Java

- New -- declared, but not yet started
- Runnable -- ready to run
- Running -- currently running
- Blocked -- on I/O, wait on monitor, sleep, join
- Dead -- run has ended

Concurrency in Java



Monitor in Java

```
public class BoundedBuffer {
   protected int numSlots;
   private int[] buffer;
   private int takeOut = 0, putIn = 0;
   private int count=0;

   public BoundedBuffer(int numSlots) {
      if(numSlots < 0) {
         throw new IllegalArgumentException(
                                        "numSlots <= 0");
      }
      this.numSlots = numSlots;
      buffer = new int[numSlots];
   }
```

From Mitchell, hmwk 14.7

```
    public synchronized void put(int value)
                          throws InterruptedException {
       while (count == numSlots) wait();
       buffer[putIn] = value;
       putIn = (putIn + 1) % numSlots;
       count++;
       notifyAll();
    }

    public synchronized int get()
                          throws InterruptedException {
       while (count == 0) wait();
       int value = buffer[takeOut];
       takeOut = (takeOut + 1) % numSlots;
       count--;
       notifyAll();
       return value;
    }
}
```

Java Critique

- Brinch Hansen - designer w/Hoare of Monitors hates Java concurrency!
  - Doesn't require programmer to have all methods synchronized,
  - can leave instance variables accessible w/out going through synchronized methods, it is easy to mess up access w/concurrent programs.
  - Felt that should have had a monitor class that would only allow synchronized methods.

Java Threads

- Portable since part of language
  - Easier to use than C system calls
  - Garbage collector runs in separate thread
- Difficult to combine sequential/concurrent code
  - Using sequential code in concurrent -- may not work
  - Java collection classes have synchronized wrappers!
- Using concurrent in sequential programs
  - Useless synchronization
  - 10-20% useless overhead

Rough Spots

- Fairness not guaranteed
  - Choose arbitrarily among equal priority threads
- Wait set is not FIFO queue
  - notifyAll notifies all waiting threads, not necessarily highest priority, longest-waiting, etc.
- Nested monitor problem can cause deadlock.

Nested Monitor Lockout Problem

```
class Stack {
   LinkedListlist = new LinkedList();
   public synchronized void push(Objectx) {
      synchronized(list) {
         list.addLast( x ); notify();
       } }
   public synchronized Object pop() {
      synchronized(list) {
         if( list.size() <= 0 ) wait();
         return list.removeLast();
      } }
}
```

Releases lock on Stack object but not lock on list; a push from another thread will deadlock

Java 5: util.concurrent

- Doug Lea utility classes
  - A few general purpose interfaces
  - Implementations tested over several years
- Principal interfaces & implementations
  - Sync -- protocols to acquire and release locks,
    - e.g. Semaphore w/ acquire, release methods
  - BlockingQueue -- classes to insert and delete objects
    - support put, take that block (like bounded buffer)
  - Executor -- executes Runnable tasks
    - You provide control of threads

Java 5 Concurrency Features

```
class BoundedBuffer {   <- array based queue
   final Lock lock = new ReentrantLock();
   final Condition notFull  = lock.newCondition();
   final Condition notEmpty = lock.newCondition();

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

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

Java 5 Concurrency cont.

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

- Advantage: Separate queues for nonEmpty and nonFull conditions on same lock.