CSE373: Data Structures & Algorithms
Lecture 21: Introduction to Multithreading & Fork-Join Parallelism

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Changing a major assumption

So far most or all of your study of computer science has assumed

*One thing happened at a time*

Called *sequential programming* – everything part of one sequence

Removing this assumption creates major challenges & opportunities

- Programming: Divide work among *threads of execution* and coordinate (*synchronize*) among them
- Algorithms: How can parallel activity provide speed-up (more *throughput*: work done per unit time)
- Data structures: May need to support *concurrent access* (multiple threads operating on data at the same time)
A simplified view of history

Writing correct and efficient multithreaded code is often much more difficult than for single-threaded (i.e., sequential) code
  – Especially in common languages like Java and C
  – So typically stay sequential if possible

From roughly 1980-2005, desktop computers got exponentially faster at running sequential programs
  – About twice as fast every couple years

But nobody knows how to continue this
  – Increasing clock rate generates too much heat
  – Relative cost of memory access is too high
  – But we can keep making “wires exponentially smaller” (Moore’s “Law”), so put multiple processors on the same chip (“multicore”)
What to do with multiple processors?

- Next computer you buy will likely have 4 processors
  - Wait a few years and it will be 8, 16, 32, …
  - The chip companies have decided to do this (not a “law”)

- What can you do with them?
  - Run multiple totally different programs at the same time
    - Already do that? Yes, but with time-slicing
  - Do multiple things at once in one program
    - Our focus – more difficult
    - Requires rethinking everything from asymptotic complexity to how to implement data-structure operations
Parallelism vs. Concurrency

Note: Terms not yet standard but the perspective is essential
– Many programmers confuse these concepts

**Parallelism:**
Use extra resources to solve a problem faster

**Concurrency:**
Correctly and efficiently manage access to shared resources

There is some connection:
– Common to use *threads* for both
– If parallel computations need access to shared resources, then the concurrency needs to be managed

We will just do a little parallelism, avoiding concurrency issues
An analogy

CS1 idea: A program is like a recipe for a cook
   – One cook who does one thing at a time! *(Sequential)*

Parallelism:
   – Have lots of potatoes to slice?
   – Hire helpers, hand out potatoes and knives
   – But too many chefs and you spend all your time coordinating

Concurrency:
   – Lots of cooks making different things, but only 4 stove burners
   – Want to allow access to all 4 burners, but not cause spills or incorrect burner settings
Parallelism Example

Parallelism: Use extra resources to solve a problem faster

Pseudocode for array sum

– Bad style for reasons we’ll see, but may get roughly 4x speedup

```java
int sum(int[] arr){
    res = new int[4];
    len = arr.length;
    FORALL(i=0; i < 4; i++) { //parallel iterations
        res[i] = sumRange(arr,i*len/4,(i+1)*len/4);
    }
}
int sumRange(int[] arr, int lo, int hi) {
    result = 0;
    for(j=lo; j < hi; j++)
        result += arr[j];
    return result;
}
```
Concurrency Example

Concurrency: Correctly and efficiently manage access to shared resources

Pseudocode for a shared chaining hashtable
- Prevent bad interleavings (correctness)
- But allow some concurrent access (performance)

```java
class Hashtable<K, V> {
    ...
    void insert(K key, V value) {
        int bucket = ...;
        prevent-other-inserts/lookups in table[bucket]
        do the insertion
        re-enable access to table[bucket]
    }
    V lookup(K key) {
        (similar to insert, but can allow concurrent lookups to same bucket)
    }
}
```
Shared memory

The model we will assume is shared memory with explicit threads
  – Not the only approach, may not be best, but time for only one

Old story: A running program has
  – One program counter (current statement executing)
  – One call stack (with each stack frame holding local variables)
  – Objects in the heap created by memory allocation (i.e., new)
    • (nothing to do with data structure called a heap)
  – Static fields

New story:
  – A set of threads, each with its own program counter & call stack
    • No access to another thread’s local variables
  – Threads can (implicitly) share static fields / objects
    • To communicate, write somewhere another thread reads
Shared memory

Threads each have own unshared call stack and current statement
- (pc for “program counter”)
- local variables are numbers, null, or heap references

Any objects can be shared, but most are not
Our Needs

To write a shared-memory parallel program, need new primitives from a programming language or library

- Ways to create and *run multiple things at once*
  - Let’s call these things threads

- Ways for threads to *share memory*
  - Often just have threads with references to the same objects

- Ways for threads to *coordinate (a.k.a. synchronize)*
  - A way for one thread to wait for another to finish
  - [Other features needed in practice for concurrency]
Java basics

Learn a couple basics built into Java via java.lang.Thread
   – But for style of parallel programming we’ll advocate, do not use these threads; use Java 7’s ForkJoin Framework instead

To get a new thread running:
1. Define a subclass C of java.lang.Thread, overriding run
2. Create an object of class C
3. Call that object’s start method
   - start sets off a new thread, using run as its “main”

What if we instead called the run method of C?
   - This would just be a normal method call, in the current thread

Let’s see how to share memory and coordinate via an example…
Parallelism idea

• Example: Sum elements of a large array
• Idea: Have 4 threads simultaneously sum 1/4 of the array
  – Warning: This is an inferior first approach

– Create 4 thread objects, each given a portion of the work
– Call start() on each thread object to actually run it in parallel
– Wait for threads to finish using join()
– Add together their 4 answers for the final result
class SumThread extends java.lang.Thread {

    int lo; // arguments
    int hi;
    int[] arr;

    int ans = 0; // result

    SumThread(int[] a, int l, int h) {
        lo=l; hi=h; arr=a;
    }

    public void run() { //override must have this type
        for(int i=lo; i < hi; i++)
            ans += arr[i];
    }
}

Because we must override a no-arguments/no-result run, we use fields to communicate across threads
class SumThread extends java.lang.Thread {
    int lo, int hi, int[] arr; // arguments
    int ans = 0; // result
    SumThread(int[] a, int l, int h) { ... } // override
}

int sum(int[] arr) { // can be a static method
    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);
    for (int i=0; i < 4; i++) // combine results
        ans += ts[i].ans;
    return ans;
}
Second attempt (still wrong)

class SumThread extends java.lang.Thread {
    int lo, int hi, int[] arr; // arguments
    int ans = 0; // result
    SumThread(int[] a, int l, int h) { ... }
    public void run(){ ... } // override
}

int sum(int[] arr){ // can be a static method
    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
        ans += ts[i].ans;
    }
    return ans;
}
class SumThread extends java.lang.Thread {
    int lo, int hi, int[] arr; // arguments
    int ans = 0; // result
    SumThread(int[] a, int l, int h) { ... }
    public void run(){ ... } // override
}

int sum(int[] arr){ // can be a static method
    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();
    }
    for(int i=0; i < 4; i++) { // combine results
        ts[i].join(); // wait for helper to finish!
        ans += ts[i].ans;
    }
    return ans;
}
Join (not the most descriptive word)

• The Thread class defines various methods you could not implement on your own
  – For example: start, which calls run in a new thread

• The join method is valuable for coordinating this kind of computation
  – Caller blocks until/unless the receiver is done executing (meaning the call to run returns)
  – Else we would have a race condition on ts[i].ans

• This style of parallel programming is called “fork/join”

• Java detail: code has 1 compile error because join may throw java.lang.InterruptedIOException
  – In basic parallel code, should be fine to catch-and-exit
Shared memory?

• Fork-join programs (thankfully) do not require much focus on sharing memory among threads

• But in languages like Java, there is memory being shared. In our example:
  – lo, hi, arr fields written by “main” thread, read by helper thread
  – ans field written by helper thread, read by “main” thread

• When using shared memory, you must avoid race conditions
  – We will stick with join to do so
A better approach

Several reasons why this is a poor parallel algorithm

1. Want code to be reusable and efficient across platforms
   – “Forward-portable” as core count grows
   – So at the very least, parameterize by the number of threads

```java
int sum(int[] arr, int numTs) {
    int ans = 0;
    SumThread[] ts = new SumThread[numTs];
    for (int i=0; i < numTs; i++) {
        ts[i] = new SumThread(arr, (i*arr.length)/numTs,
                               ((i+1)*arr.length)/numTs);
        ts[i].start();
    }
    for (int i=0; i < numTs; i++) {
        ts[i].join();
        ans += ts[i].ans;
    }
    return ans;
}
```
A Better Approach

2. Want to use (only) processors “available to you now”
   - Not used by other programs or threads in your program
     • Maybe caller is also using parallelism
     • Available cores can change even while your threads run
   - If you have 3 processors available and using 3 threads would take time $x$, then creating 4 threads would take time $1.5x$
     • Example: 12 units of work, 3 processors
       – Work divided into 3 parts will take 4 units of time
       – Work divided into 4 parts will take 3*2 units of time

```c
// numThreads == numProcessors is bad
// if some are needed for other things
int sum(int[] arr, int numTs){
    ...
}
```
A Better Approach

3. Though unlikely for \texttt{sum}, in general subproblems may take significantly different amounts of time

- Example: Apply method $f$ to every array element, but maybe $f$ is much slower for some data items
  - Example: Is a large integer prime?

- If we create 4 threads and all the slow data is processed by 1 of them, we won’t get nearly a 4x speedup
  - Example of a load imbalance
A Better Approach

The counterintuitive (?) solution to all these problems is to use lots of threads, far more than the number of processors

- But this will require changing our algorithm
- [And using a different Java library]

1. Forward-portable: Lots of helpers each doing a small piece
2. Processors available: Hand out “work chunks” as you go
   - If 3 processors available and have 100 threads, then ignoring constant-factor overheads, extra time is < 3%
3. Load imbalance: No problem if slow thread scheduled early enough
   - Variation probably small anyway if pieces of work are small


Naïve algorithm is poor

Suppose we create 1 thread to process every 1000 elements

```java
int sum(int[] arr){
    ...
    int numThreads = arr.length / 1000;
    SumThread[] ts = new SumThread[numThreads];
}
```

Then combining results will have $\frac{\text{arr.length}}{1000}$ additions

- Linear in size of array (with constant factor 1/1000)
- Previously we had only 4 pieces (constant in size of array)

In the extreme, if we create 1 thread for every 1 element, the loop to combine results has length-of-array iterations

- Just like the original sequential algorithm
A better idea

This is straightforward to implement using divide-and-conquer
- Parallelism for the recursive calls
Divide-and-conquer to the rescue!

class SumThread extends java.lang.Thread {
    int lo; int hi; int[] arr; // arguments
    int ans = 0; // result
    SumThread(int[] a, int l, int h) { ... }
    public void run(){ // override
        if(hi - lo < SEQUENTIAL CUTOFF)
            for(int i=lo; i < hi; i++)
                ans += arr[i];
        else {
            SumThread left = new SumThread(arr,lo,(hi+lo)/2);
            SumThread right = new SumThread(arr,(hi+lo)/2,hi);
            left.start();
            right.start();
            left.join(); // don’t move this up a line – why?
            right.join();
            ans = left.ans + right.ans;
        }
    }
}

int sum(int[] arr){
    SumThread t = new SumThread(arr,0,arr.length);
    t.run();
    return t.ans;
}
Divide-and-conquer really works

- The key is divide-and-conquer parallelizes the result-combining
  - *If* you have enough processors, total time is height of the tree: $O(\log n)$ (optimal, exponentially faster than sequential $O(n)$)
  - Next lecture: consider reality of $P << n$ processors
Being realistic

• In theory, you can divide down to single elements, do all your result-combining in parallel and get optimal speedup
  – Total time \( O\left(\frac{n}{\text{numProcessors}} + \log n\right) \)

• In practice, creating all those threads and communicating swamps the savings, so:
  – Use a sequential cutoff, typically around 500-1000
    • Eliminates almost all the recursive thread creation (bottom levels of tree)
    • Exactly like quicksort switching to insertion sort for small subproblems, but more important here
  – Do not create two recursive threads; create one and do the other “yourself”
    • Cuts the number of threads created by another 2x
Being realistic, part 2

• Even with all this care, Java’s threads are too “heavyweight”
  – Constant factors, especially space overhead
  – Creating 20,000 Java threads just a bad idea 😞

• The ForkJoin Framework is designed to meet the needs of divide-and-conquer fork-join parallelism
  – In the Java 7 standard libraries
  – Library’s implementation is a fascinating but advanced topic
    • Next lecture will discuss its guarantees, not how it does it
  – Names of methods and how to use them slightly different