CSE373: Data Structures and Algorithms

Fork-Join Parallelism

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This lecture material represents the work of multiple instructors at the University of Washington. Thank you to all who have contributed!

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 (your current one might already)
  - 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

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* - belong to the class and not an instance (or object) of the class. Only one for all instances of a class.

New story:

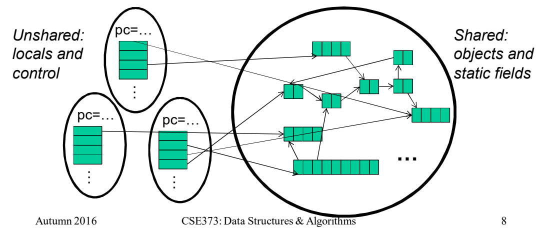
- A set of *threads*, each with its own program counter & call stack
  - No access to another thread's local variables
- Threads can (implicitly) share static fields / objects
  - To *communicate*, write somewhere another thread reads

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"

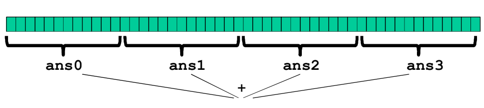
What if we instead called the **`run`** method of **`C`**?

- 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, but it's usually good to start with something naïve works



- 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*

First attempt, part 1

```
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

First attempt, continued (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);
  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;
}
```


Third attempt (correct in spirit)

```
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` (answer would depend on what finishes first)
- This style of parallel programming is called "fork/join"
- Java detail: code has 1 compile error because `join` may throw `java.lang.InterruptedException`
  - 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

```
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

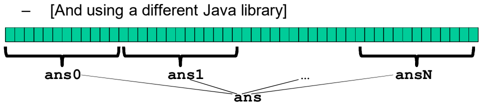
```
// numThreads == numProcessors is bad
// if some are needed for other things
int sum(int[] arr, int numTs){
  …
}
```


A Better Approach

3. Though unlikely for **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
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

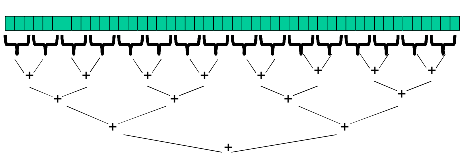
Suppose we create 1 thread to process every 1000 elements

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

Then combining results will have **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



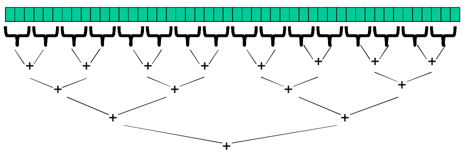
This is straightforward to implement using divide-and-conquer
- Parallelism for the recursive calls

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: $O(\texttt{log}\ n)$ (optimal, exponentially faster than sequential $O(n)$)



Being realistic

- In theory, you can divide down to single elements, do all your result-combining in parallel and get optimal speedup
  - Total time $O(n/numProcessors + \texttt{log}\ n)$
- 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 is just a bad idea ☹
- The ForkJoin Framework is designed to meet the needs of divide-and-conquer fork-join parallelism
  - In the Java 7 (and 8) standard libraries
  - Library's implementation is a fascinating but advanced topic
  - Names of methods and how to use them slightly different