CSE332: Data Abstractions

Lecture 18: Introduction to Multithreading and Fork-Join Parallelism

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Changing a major assumption

So far in 142, 143, 311, and 332, we have 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 Example

Parallelism: Increasing throughput by using additional computational resources (code running simultaneously)

Example in *pseudocode* (not Java, yet): sum elements of an array

- This example is bad style for reasons we'll see
- If you had 4 processors, might get roughly 4x speedup

```
int sum(int[] arr){
  res = new int[4];
  len = arr.length;
  FORALL(i=0; i < 4; i++) { //parallel iterations
    res[i] = help(arr,i*len/4,(i+1)*len/4);
  }
  return res[0]+res[1]+res[2]+res[3];
}
int help(int[] arr, int lo, int hi) {
   result = 0;
   for(j=lo; j < hi; j++)
      result += arr[j];
   return result;
}
```


Concurrency Example

Concurrency: Allowing simultaneous or interleaved access to shared resources from multiple clients

Example in *pseudocode* (not Java, yet): chaining hashtable

- Essential correctness issue is preventing bad interleavings
- Essential performance issue not preventing good concurrency

```
class Hashtable<K,V> {
   …
   Hashtable(Comparator<K> c, Hasher<K> h) { … };
   void insert(K key, V value) {
      int bucket = …;
      prevent-other-inserts/lookups in table[bucket];
      do the insertion
      re-enable access to arr[bucket];
   }
   V lookup(K key) {
      (like insert, but can allow concurrent
       lookups to same bucket)
   }
}
```


Parallelism vs. Concurrency

Note: These terms are not yet standard, but the difference in perspective is essential

- Many programmers confuse them

Parallelism: Use more resources for a faster answer

Concurrency: Correctly and efficiently allow simultaneous access

There is some connection:

- Many programmers use threads for both
- If parallel computations need access to shared resources, then something needs to manage the concurrency

CSE332: Next 3-4 lectures on parallelism, then 3-4 on concurrency

An analogy

CSE142 idea: Writing a program is like writing a recipe for a cook

- One cook who does one thing at a time!

Parallelism:

- Have lots of potatoes to slice?
- Hire helpers, hand out potatoes and knives
- But not too many chefs or you spend all your time coordinating

Concurrency:

- Lots of cooks making different things, but only 4 stove burners
- Want to allow simultaneous 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

Old story: A running program has

- One *call stack* (with each *stack frame* holding local variables)
- One *program counter* (current statement executing)
- Static fields
- Objects (created by **new**) in the *heap* (nothing to do with heap data structure)

New story:

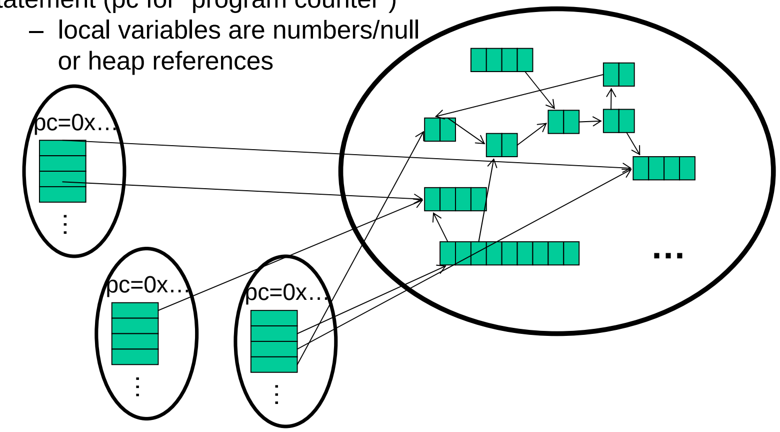
- A set of *threads*, each with its own call stack & program counter
  - No access to another thread's local variables
- Threads can (implicitly) share static fields / objects
  - To *communicate*, write somewhere another thread reads

Shared memory

Threads, each 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



Other models

We will focus on shared memory, but you should know several other models exist and have their own advantages

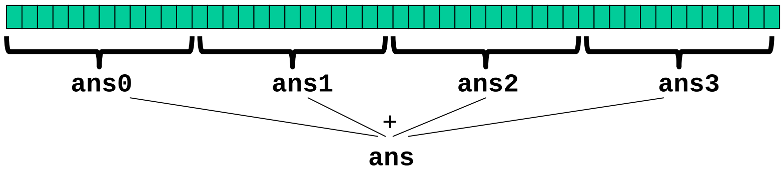
- Message-passing: Each thread has its own collection of objects. Communication is via explicit messages; language has primitives for sending and receiving them.
  - Cooks working in separate kitchens, with telephones
- Dataflow: Programmers write programs in terms of a DAG and a node executes after all of its predecessors in the graph
  - Cooks wait to be handed results of previous steps
- Data parallelism: Have primitives for things like "apply function to every element of an array in parallel"
- …

Some Java basics

- Many languages/libraries provide primitives for creating threads and synchronizing them
- Will show you how Java does it
  - Many primitives will be delayed until we study concurrency
  - We will not use Java threads much in project 3 for reasons lecture will explain, but it's still worth seeing them first
- Steps to creating another thread:
  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
     - Not `run`, which would just be a normal method call

Parallelism idea

- Example: Sum elements of an array (presumably large)
- Use 4 threads, which each sum 1/4 of the array



- Steps:
  – Create 4 thread objects, assigning 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 at parallelism: wrong!

```
class SumThread extends java.lang.Thread {
  int lo; // fields to know what to do
  int hi;
  int[] arr;
  int ans = 0; // for communicating result
  SumThread(int[] a, int l, int h) {
    lo=l; hi=h; arr=a;
  }
  public void run(){ //overriding, must have this type
    for(int i=lo; i < hi; i++)
      ans += arr[i];
  }
}
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);
  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;//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
    ans += ts[i].ans;
  return ans;
}
```


Third attempt (correct in spirit)

```
class SumThread extends java.lang.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();
  }
  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 that provide the threading primitives you could not implement on your own
  - For example: **start**, which calls **run** in a new thread
- The **join** method is one such method, essential for coordination in this kind of computation
  - Caller blocks until/unless the receiver is done executing (meaning its **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.InterruptedException**
  - In basic parallel code, should be fine to catch-and-exit

Shared memory?

- Fork-join programs (thankfully) don't require a lot of 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
  - While studying parallelism, we'll stick with **join**
  - With concurrency, we'll learn other ways to synchronize

Now forget a lot of what we just did ☺

Several reasons why this is a poor way to sum an array in parallel!

1. Want code to be reusable and efficient across platforms
   - "Forward-portable" as core count grows

So at the *very* least, make the number of threads a parameter

```
int sum(int[] arr, int numThreads){
  … // note: shows idea, but has integer-division bug
  int subLen = arr.length / numThreads;
  SumThread[] ts = new SumThread[numThreads];
  for(int i=0; i < numThreads; i++){
   ts[i] = new SumThread(arr,i*subLen,(i+1)*subLen);
   ts[i].start();
  }
  for(int i=0; i < numThreads; i++) {
    …
  }
  …
```


Now forget a lot of what we just did ☺

2. Want to effectively use processors "available to you *now*"
   - Not being used by other programs or threads in your program
     - Can change even while your threads are running
     - Maybe caller is also using parallelism already
   - If you have 3 processors available and using 3 threads would take time **X**, then creating 4 threads would take time **1.5X**

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

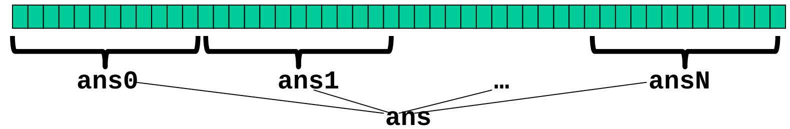
Now forget a lot of what we just did ☺

3. Though unlikely for **`sum`**, in general different threads 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 than others
     - 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

Now forget a lot of what we just did ☺

The perhaps counter-intuitive 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 for constant-factor reasons, abandoning Java's threads



1. Forward-portable: Lots of threads each doing a small piece
2. Processors available: Hand out threads 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

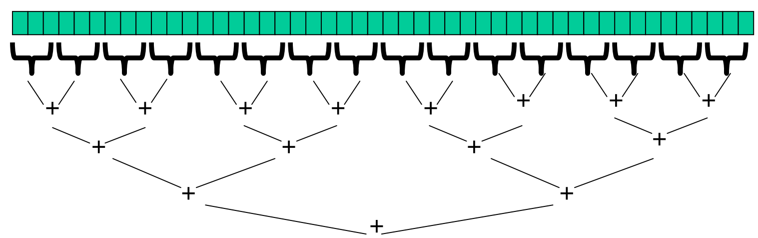
Naïve algorithm doesn't work

- Suppose we create 1 thread to process every 100 elements

```
int sum(int[] arr){
  …
  int numThreads = arr.length / 100;
  SumThread[] ts = new SumThread[numThreads];
  …
}
```

- Then combining results will have **`arr.length / 100`** additions to do – still linear in size of array
- In the extreme, suppose we create a thread to process every 1 element – then we're back to where we started even though we said more threads was better

A better idea



This is straightforward to implement using divide-and-conquer

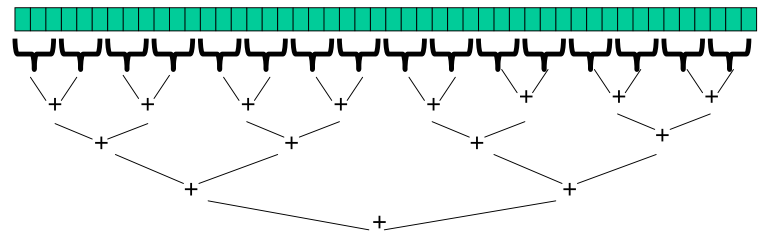
- Parallelism for the recursive calls

Divide-and-conquer to the rescue!

```
class SumThread extends java.lang.Thread {
  int lo; int hi; int[] arr;//fields to know what to do
  int ans = 0; // for communicating result
  SumThread(int[] a, int l, int h) { … }
  public void run(){
    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 depth of the tree: $O(\textbf{log } n)$ (optimal, exponentially faster than sequential $O(n)$)
  - Next lecture: study reality of $\mathbf{P} < O(n)$ processors
- Will write all our parallel algorithms in this style
  - But using a special library designed for exactly this
    - Takes care of scheduling the computation well
  - Often relies on operations being associative like +



Being realistic

- In theory, you can divide down to single elements, do all your result-combining in parallel and get optimal speedup
  - Total time $O(n/numProcessors + \textbf{log } n)$
- In practice, creating all that inter-thread communication swamps the savings, so:
  - Use a sequential cutoff, typically around 500-1000
    - As in quicksort, eliminates almost all recursion, but here it is even more important
  - Don't create two recursive threads; create one and do the other "yourself"
    - Cuts the number of threads created by another 2x

Half the threads

```
// wasteful: don't
SumThread left  = …
SumThread right = …
left.start();
right.start();
left.join();
right.join();
ans=left.ans+right.ans;
```

```
// better: do
SumThread left  = …
SumThread right = …
// order of next 4 lines
// essential – why?
left.start();
right.run();
left.join();
ans=left.ans+right.ans;
```

- If a *language* had built-in support for fork-join parallelism, I would expect this hand-optimization to be unnecessary
- But the *library* we are using expects you to do it yourself
  - And the difference is surprisingly substantial
- Again, no difference in theory

That library, finally

- Even with all this care, Java's threads are too "heavy-weight"
  - 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
  - Will be in Java 7 standard libraries, but available in Java 6 as a downloaded **`.jar`** file
  - Section will focus on pragmatics/logistics
  - Similar libraries available for other languages
    - C/C++: Cilk (inventors), Intel's Thread Building Blocks
    - C#: Task Parallel Library
    - …
  - How the library works is fascinating, but a bit beyond CSE332

Different terms, same basic idea

To use the ForkJoin Framework:

- A little standard set-up code (e.g., create a **`ForkJoinPool`**)

Don't subclass **`Thread`**	Do subclass **`RecursiveTask<V>`**
Don't override **`run`**	Do override **`compute`**
Do not use an **`ans`** field	Do return a **`V`** from **`compute`**
Don't call **`start`**	Do call **`fork`**
Don't just call **`join`**	Do call **`join`** which returns answer
Don't call **`run`** to hand-optimize	Do call **`compute`** to hand-optimize

Example: final version (missing imports)

```
class SumArray extends RecursiveTask<Integer> {
  int lo; int hi; int[] arr;//fields to know what to do
  SumArray(int[] a, int l, int h) { … }
  protected Integer compute(){// return answer
    if(hi – lo < SEQUENTIAL_CUTOFF) {
      int ans = 0;
      for(int i=lo; i < hi; i++)
        ans += arr[i];
      return ans;
    } else {
      SumArray left = new SumArray(arr,lo,(hi+lo)/2);
      SumArray right= new SumArray(arr,(hi+lo)/2,hi);
      left.fork();
      int rightAns = right.compute();
      int leftAns  = left.join();
      return leftAns + rightAns;
    }
  }
}
static final ForkJoinPool fjPool = new ForkJoinPool();
int sum(int[] arr){
  return fjPool.invoke(new SumArray(arr,0,arr.length));
}
```


Getting good results in practice

- Sequential threshold
  - Library documentation recommends doing approximately 100-5000 basic operations in each "piece" of your algorithm
- Library needs to "warm up"
  - May see slow results before the Java virtual machine re-optimizes the library internals
  - Put your computations in a loop to see the "long-term benefit"
- Wait until your computer has more processors ☺
  - Seriously, overhead may dominate at 4 processors, but parallel programming is likely to become much more important
- Beware memory-hierarchy issues
  - Won't focus on this, but often crucial for parallel performance