COMP 322: Fundamentals of Parallel Programming

Lecture 14: Iterative Averaging Revisited, SPMD pattern

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Worksheet #13 solution: Parallelism in Java Streams, Parallel Prefix Sums

1. What output will the following Java Streams code print?

```
C1          C2
      or
C2          C1
```

The sorted() operation is a no-op if the printing is performed in parallel!

2. Which stream operation in this example could benefit from a parallel prefix sum implementation, and why?

The filter operation since parallel prefix can be used to compute the indices in the output array

```
Arrays
  .asList(“a1", "a2", "b1", "c2", "c1")
  .parallelStream()
  .filter(s -> s.startsWith(“c"))
  .sorted()
  .map(String::toUpperCase)
  .forEach(System.out::println);
```

Recap: Parallel Filter Operation

[Credits: David Walker and Andrew W. Appel (Princeton), Dan Grossman (U. Washington)]

Given an array `input`, produce an array `output` containing only elements such that `f(elt)` is `true`, i.e., output = input.parallelStream.filter(f).toArray

Example: `input [17, 4, 6, 8, 11, 5, 13, 19, 0, 24]`

```
f: is elt > 10
output [17, 11, 13, 19, 24]
```

Parallelizable?

- Finding elements for the output is easy
- But getting them in the right place seems hard

Recap: Parallel prefix to the rescue

1. Parallel map to compute a bit-vector for true elements (can use Java streams)

```
input  [17, 4, 6, 8, 11, 5, 13, 19, 0, 24]
bits   [1,  0, 0, 0,  1, 0,  1,  1, 0,  1]
```

2. Parallel-prefix sum on the bit-vector (not available in Java streams)

```
bitsum [1,  1, 1, 1,  2, 2,  3,  4, 4,  5]
```

3. Parallel map to produce the output (can use Java streams)

```
output [17, 11, 13, 19, 24]
```

```
output = new array of size bitsum[n-1]
FORALL(i=0; i < input.length; i++){
  if(bits[i]==1)
    output[bitsum[i]-1] = input[i];
}
```

One-Dimensional Iterative Averaging Revisited

- Initialize a one-dimensional array of (n+2) double's with boundary conditions, myVal[0] = 0 and myVal[n+1] = 1.
- In each iteration, each interior element myVal[i] in 1..n is replaced by the average of its left and right neighbors.
  - —Two separate arrays are used in each iteration, one for old values and the other for the new values
- After a sufficient number of iterations, we expect each element of the array to converge to myVal[i] = (myVal[i-1]+myVal[i+1])/2, for all i in 1..n

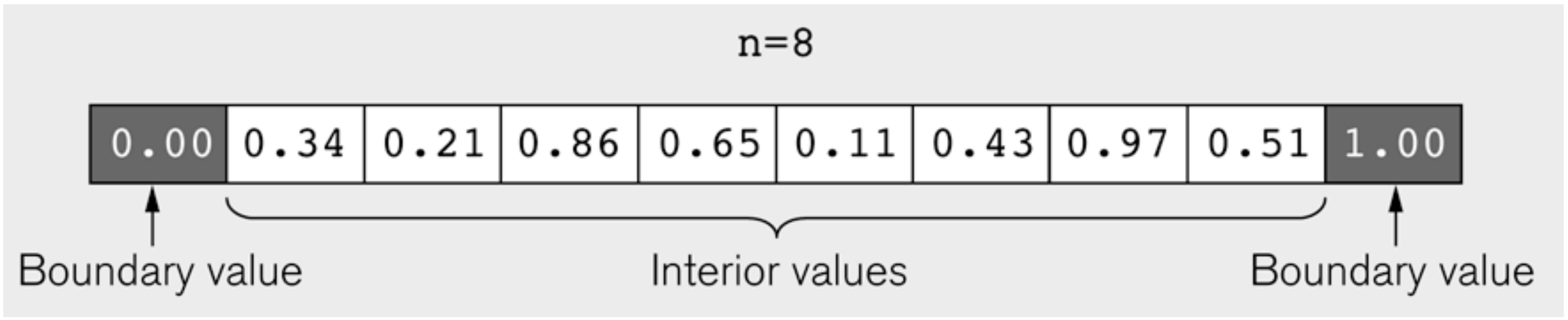


Illustration of an intermediate step for n = 8 (source: Figure 6.19 in Lin-Snyder book)

Iterative Averaging structure is akin to that of a Finite Difference solution to the One-Dimensional Heat Equation

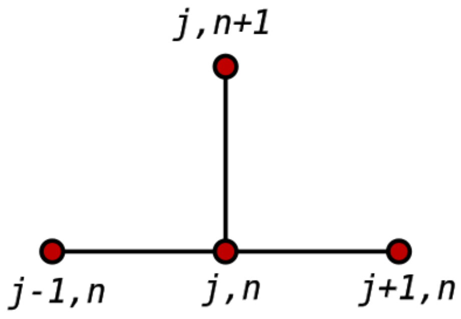
- In the 1D heat equation, u(j,t) represents the temperature at position j in a 1D object at nth time step (different use of "n" from our code)
- Recall that for a "properly-behaved" function *f*, and a sufficiently small *h*, we can approximate the first derivative of *f* as follows:

$$f'(a) \approx \frac{f(a+h) - f(a)}{h}$$

- We can use this principle in both space and time to compute
  - u(j,n+1) = f(u(j-1,n), u(j,n), u(j+1,n))

for multiple time steps n until we reach a convergence with an acceptably small error between time steps

- These algorithms are also referred to as "stencil codes"
- Source: http://en.wikipedia.org/wiki/Finite_difference_method
- See also: https://en.wikipedia.org/wiki/Heat_equation



HJ code for One-Dimensional Iterative Averaging using nested `forseq-forall` structure (Lecture 11)

```
double[] myVal=new double[n+2]; myVal[n+1] = 1;
double[] myNew=new double[n+2]; myNew[n+1] = myVal[n+1];
forseq(0, m-1, (iter) -> {
  // Compute MyNew as function of input array MyVal
  forall(1, n, (j) -> { // Create n tasks
     myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
  }); // forall
  // Swap myVal & myNew;
   temp=myVal; myVal=myNew; myNew=temp;
   // myNew becomes input array for next iteration
}); // for
```

Converting forseq-forall version (Slide 7) into a forall-forseq version with barriers

```
double[] gVal=new double[n+2]; gVal[n+1] = 1;
double[] gNew=new double[n+2];
forallPhased(1, n, (j) -> { // Create n tasks
  // Initialize myVal and myNew as local pointers
  double[] myVal = gVal; double[] myNew = gNew;
  forseq(0, m-1, (iter) -> {
    // Compute MyNew as function of input array MyVal
    myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
    next(); // Barrier before next iteration of iter loop
    // Swap local pointers, myVal and myNew
    double[] temp=myVal; myVal=myNew; myNew=temp;
    // myNew becomes input array for next iteration
   }); // forseq
}); // forall
```

General Approach for Iteration Grouping (Loop Chunking)

Without chunking:

```
for (iter : [0:iterations-1]) {
  forall (j : [1:n])
    myNew[j] = (myVal[j-1] + myVal[j+1])/2;
  Swap myNew and myVal
}
```

With chunking (replace “forall” by “forall-for”:

```
for (iter : [0:iterations-1]) {
  forall (g : [0:ng-1])
    for(j : myGroup(g,[1:n],ng)
      myNew[j] = (myVal[j-1] + myVal[j+1])/2;
  Swap myNew and myVal
}
```

Example: HJ code for One-Dimensional Iterative Averaging with Slide 7 code w/ chunking (Lecture 11)

```
double[] myVal=new double[n+2]; myVal[n+1] = 1;
double[] myNew=new double[n+2]; myNew[n+1] = myVal[n+1];
int nc = numWorkerThreads();
forseq(0, m-1, (iter) -> {
  // Compute MyNew as function of input array MyVal
  forallChunked(1, n, n/nc, (j) -> { // Create nc tasks
      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
  }); // forallChunked
  temp=myVal; myVal=myNew; myNew=temp;// Swap myVal & myNew;
  // myNew becomes input array for next iteration
}); // for
```

General Approach for Iteration Grouping with Barriers

Barrier-based solution:

// Note that iter-loop is inserted between forall-g and for-j loops

```
forall (g : [0:ng-1])
  for (iter : [0:iterations-1]) {
      for(j : myGroup(g,[1:n],ng)
         myNew[j] = (myVal[j-1] + myVal[j+1])/2;
      next; // Barrier
      Swap myNew and myVal
  } // for iter
```

Also referred to as a "single program multiple data" (SPMD) pattern

Chunking the forall loop in Slide 8 — inner chunked loop goes inside forseq-iter loop

```
double[] gVal=new double[n+2]; gVal[n+1] = 1;
double[] gNew=new double[n+2];
HjRegion1D iterSpace = newRectangularRegion1D(1,n);
int nc = numWorkerThreads();
forallPhased(0, nc-1, (jj) -> { // Create nc tasks
  // Initialize myVal and myNew as local pointers
  double[] myVal = gVal; double[] myNew = gNew;
  forseq(0, m-1, (iter) -> {
    forseq(myGroup(jj,iterSpace,nc), (j) -> {
      // Compute MyNew as function of input array MyVal
      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
    }); // forseq
    next(); // Barrier before executing next iteration of iter loop
    // Swap local pointers, myVal and myNew
    double[] temp=myVal; myVal=myNew; myNew=temp;
    // myNew becomes input array for next iter
  }); // forseq
}); // forall
```

Single Program Multiple Data (SPMD)

Basic idea

- Run the same code (program) on P workers
- Use the “rank” --- an ID ranging from 0 to (P-1) --- to determine what data is processed by which worker
  - Hence, “single-program” and “multiple-data”
  - Rank is equivalent to index in a top-level “forall (point[i] : [0:P-1])” loop
- Lower-level programming model than dynamic async/finish parallelism
  - Programmer’s code is essentially at the worker level (each forall iteration is like a worker), and work distribution is managed by programmer by using barriers and other synchronization constructs
  - Harder to program but can be more efficient for restricted classes of applications (e.g. for OneDimAveraging, but not for NQueens)
- Convenient for hardware platforms that are not amenable to efficient dynamic task parallelism
  - General-Purpose Graphics Processing Unit (GPGPU) accelerators
  - Distributed-memory parallel machines

Slide 12 viewed as exemplar of SPMD pattern

```
double[] gVal=new double[n+2]; gVal[n+1] = 1;
double[] gNew=new double[n+2];
HjRegion1D iterSpace = newRectangularRegion1D(1,m);
int nc = numWorkerThreads();
forallPhased(1, nc, (jj) -> { // Create nc tasks
  // Initialize myVal and myNew as local pointers
  double[] myVal = gVal; double[] myNew = gNew;
  forseq(0, m-1, (iter) -> {
    forseq(myGroup(jj,iterSpace,nc), (j) -> {
      // Compute MyNew as function of input array MyVal
      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
     }); // forseq
    next(); // Barrier before executing next iteration of iter loop
    // Swap local pointers, myVal and myNew
    double[] temp=myVal; myVal=myNew; myNew=temp;
    // myNew becomes input array for next iter
 }); // forseq
```

Instead of async-finish, this SPMD version creates one task per worker, uses myGroup() to distribute work, and use barriers to synchronize workers.