COMP 322: Fundamentals of Parallel Programming

Lecture 11: Multidimensional forasync loops, Chunking of parallel loops

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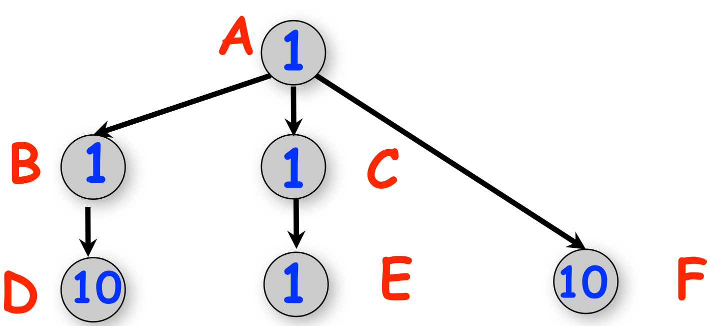
Worksheet #10 solution: Scheduling Program Q2 using Work-First & Help-First Schedulers

Work-First Schedule

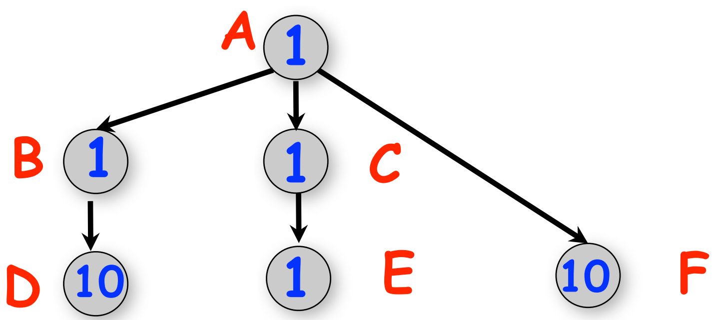
Start time	Proc 1	Proc 2
0	A	
1	C	F
2	E	F
3	B	F
4	D	F
5	D	F
6	D	F
7	D	F
8	D	F
9	D	F
10	D	F
11	D	
12	D	
13	D	

Complete work-first and help-first schedules for the program shown below (using step times from the computation graph)




```
// Program Q2
A;
finish {
  async { C; E; }
  async F;
  async { B; D; }
}
```

Worksheet #10 solution: Scheduling Program Q2 using Work-First & Help-First Schedulers (contd)




```
// Program Q2
A;
finish {
  async { C; E; }
  async F;
  async { B; D; }
}
```

Help-First Schedule

Start time	Proc 1	Proc 2
0	A	
1	B	C
2	D	E
3	D	F
4	D	F
5	D	F
6	D	F
7	D	F
8	D	F
9	D	F
10	D	F
11	D	F
12		F
13		

Outline of Today's Lecture

- **<u>Multidimensional Forasync loops</u>**

- **Chunking of parallel loops**

Acknowledgments

- COMP 322 Module 1 handout, Section 8.1, Section 9.4.

HJ's pointwise for & forasync statements

Goal: capture common for-async pattern in a single construct for multidimensional loops e.g., replace

```
finish {
  for (int I = 0 ; I < N ; I++)
    for (int J = 0 ; J < N ; J++)
      async
        for (int K = 0 ; K < N ; K++)
          C[I][J] += A[I][K] * B[K][J];
}
```

by

```
finish forasync (point [I,J] : [0:N-1,0:N-1])
  for (point[K] : [0:N-1])
    C[I][J] += A[I][K] * B[K][J];
```

Sequential Algorithm for Matrix Multiplication

$$c[i,j] = \sum_{0 \le k < n} a[i,k] * b[k,j]$$

```
// Sequential version
for (int i = 0 ; i < n ; i++)
  for (int j = 0 ; j < n ; j++)
    c[i][j] = 0;
for (int i = 0 ; i < n ; i++)
  for (int j = 0 ; j < n ; j++)
    for (int k = 0 ; k < n ; k++)
      c[i][j] += a[i][k] * b[k][j];
// Print first element of output matrix
System.out.println(c[0][0]);
```

Parallelizing the loops in Matrix Multiplication example using finish & async (Listing 27)

$$c[i,j] = \sum_{0 \le k < n} a[i,k] * b[k,j]$$

```
// Parallel version using finish & async
finish for (int i = 0 ; i < n ; i++)
  for (int j = 0 ; j < n ; j++)
    async c[i][j] = 0;
finish for (int i = 0 ; i < n ; i++)
  for (int j = 0 ; j < n ; j++)
    async for (int k = 0 ; k < n ; k++)
      c[i][j] += a[i][k] * b[k][j];
// Print first element of output matrix
System.out.println(c[0][0]);
```

Observations

- finish and async are general constructs, and are not specific to loops
  - Not easy to discern from a quick glance which loops are sequential vs. parallel
- Loops in sequential version of matrix multiplication are "perfectly nested"
  - e.g., no intervening statement between "for(i = ...)" and "for(j = ...)"
- The ordering of loops nested between finish and async is arbitrary
  - They are parallel loops and their iterations can be executed in any order

Parallelizing the loops in Matrix Multiplication example using finish, forasync & for (Listing 28)

$$c[i,j] = \sum_{0 \le k < n} a[i,k] * b[k,j]$$

```
// Parallel version using finish & forasync
finish forasync(point[i,j] : [0:n-1,0:n-1])
  c[i][j] = 0;
finish forasync(point[i,j] : [0:n-1,0:n-1]) {
  for(point[k] : [0:n-1])
    c[i][j] += a[i][k] * b[k][j];
}
// Print first element of output matrix
System.out.println(c[0][0]);
```

Observations

- The combination of perfectly nested for–for–async constructs is replaced by a single keyword, forasync
- Multiple loops can be collapsed into a single forasync with a multi-dimensional iteration space (can be 1D, 2D, 3D, ...)
- The iteration variable for a forasync is a point (integer tuple) such as [i,j].
- The loop bounds can be specified as a rectangular region (product of dimension ranges) such as [0:n−1,0:n−1]
- HJ also extends the sequential for statement so as to iterate sequentially over a rectangular region
  - Simplifies conversion between for and forasync

Summary of HJ's forasync statement

```
forasync (point [i1] : [lo1:hi1]) <body>

forasync (point [i1,i2] : [lo1:hi1,lo2:hi2]) <body>

forasync (point [i1,i2,i3] : [lo1:hi1,lo2:hi2,lo3:hi3]) <body>

. . .
```

- forasync statement creates multiple async child tasks, one per iteration of the forasync
  - all child tasks can execute <body> in parallel
  - child tasks are distinguished by index "points" ([i1], [i1,i2], …)
- <body> can read local variables from parent (copy-in semantics like async)
- forasync needs a finish for termination, just like regular async tasks
  - Later, we will learn about replacing "finish forasync" by "forall"
- In addition to its convenient syntax, parallel loop constructs are easier to manage with "chunking", compared to for-for-async structures

hj.lang.point, an index type for multi-dimensional loops

- A point is an element of an n-dimensional Cartesian space (n>=1) with integer-valued coordinates e.g., [5], [1, 2], …
  - Dimensions of a point are numbered from 0 to n-1
  - n is also referred to as the <u>rank</u> (size) of the point
- A point variable can hold values of different ranks e.g.,
  - point p; p = [1]; … p = [2,3]; …
- The following operations are defined on point-valued expression p1
  - p1.rank --- returns rank of point p1
  - p1.get(i) --- returns element i of point p1
    - Returns element (i mod p1.rank) if i < 0 or i >= p1.rank
  - p1.lt(p2), p1.le(p2), p1.gt(p2), p1.ge(p2)
    - Returns true iff p1 is lexicographically <, <=, >, or >= p2
    - Only defined when p1.rank and p1.rank are equal
- You can think of a point as an int array with additional operator support in the HJ language

Example

```
public class TutPoint {
    public static void main(String[] args) {
        point p1 = [1,2,3,4,5];
        point p2 = [1,2];
        point p3 = [2,1];
        System.out.println("p1 = " + p1 + " ; p1.rank = " + p1.rank
                            + " ; p1.get(2) = " + p1.get(2));
        System.out.println("p2 = " + p2 + " ; p3 = " + p3
                            + " ; p2.lt(p3) = " + p2.lt(p3));
    } // main()
} // TutPoint
```

Console output:

```
p1 = [1,2,3,4,5] ; p1.rank = 5 ; p1.get(2) = 3
p2 = [1,2] ; p3 = [2,1] ; p2.lt(p3) = true
```

hj.lang.region, a rectangular iteration space for multi-dimensional loops

A region is the set of *points* contained in a rectangular subspace

A region variable can hold values of different ranks e.g.,

- region R; R = [0:10]; … R = [-100:100, -100:100]; … R = [0:-1]; …

Operations

- R.rank ::= # dimensions in region;
- R.size() ::= # points in region
- R.contains(P) ::= predicate if region R contains point P
- R.contains(S) ::= predicate if region R contains region S
- R.equal(S) ::= true if region R equals region S
- R.rank(i) ::= projection of region R on dimension i (a one-dimensional region)
- R.rank(i).low() ::= lower bound of i^{th} dimension of region R
- R.rank(i).high() ::= upper bound of i^{th} dimension of region R
- R.ordinal(P) ::= ordinal value of point P in region R
- R.coord(N) ::= point in region R with ordinal value = N

Pointwise sequential for loop

- HJ extends Java's for loop to support sequential iteration over points in region R in canonical lexicographic order
  - for (point p : R) . . .
- Standard point operations can be used to extract individual index values from point p
  - for (point p : R) { int i = p.get(0); int j = p.get(1); . . . }
- Or an "exploded" syntax is commonly used instead of explicitly declaring a point variable
  - for (point [i,j] : R) { . . . }
- The exploded syntax declares the constituent variables (i, j, …) as local int variables in the scope of the for loop body

forasync examples: updates to a two-dimensional Java array

```
// Case 1: loops i,j can run in parallel
forasync (point[i,j] : [0:m-1,0:n-1]) A[i][j] = F(A[i][j]) ;


// Case 2: only loop i can run in parallel
forasync (point[i] : [1:m-1])
  for (point[j] : [1:n-1]) // Equivalent to “for (j=1;j<n;j++)”
     A[i][j] = F(A[i][j-1]) ;


// Case 3: only loop j can run in parallel
for (point[i] : [1:m-1]) // Equivalent to “for (i=1;i<m;j++)”
  finish forasync (point[j] : [1:n-1])
     A[i][j] = F(A[i-1][j]) ;
```

One-Dimensional Iterative Averaging Example

- **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] = i/(n+1)**
  - **In this case, myVal[i] = (myVal[i-1]+myVal[i+1])/2, for all i in 1..n**

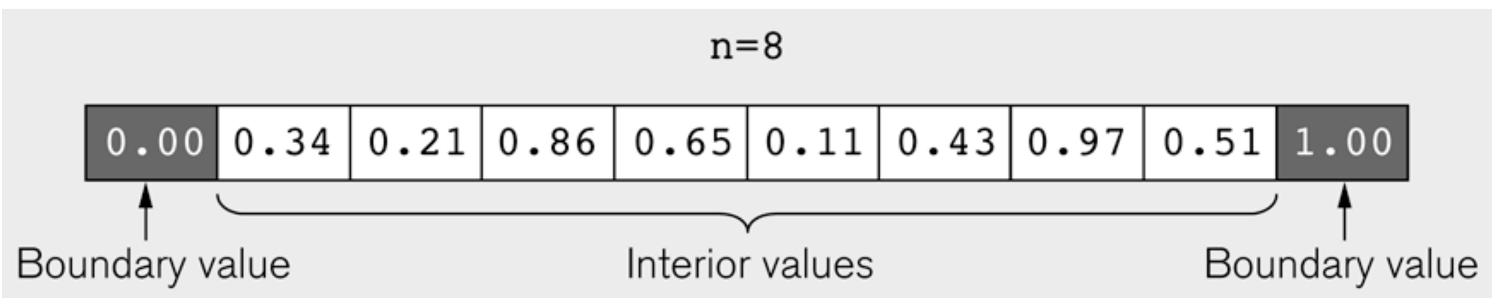


Illustration of an intermediate step for n = 8 (source: Figure 6.19 in Lin-Snyder book)

HJ code for One-Dimensional Iterative Averaging using nested for-finish-forasync structure

```
for (point [iter] : [0:m-1]) {
  // Compute MyNew as function of input array MyVal
  finish forasync (point [j] : [1:n]) { // Create n tasks
     myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
  } // finish forasync
  temp=myVal; myVal=myNew; myNew=temp;// Swap myVal & myNew;
  // myNew becomes input array for next iteration
} // for
```

How does this algorithm work? Let's try Worksheet #11!

Outline of Today's Lecture

- **Multidimensional Forasync loops**
- **Chunking of parallel loops**

Acknowledgments

- COMP 322 Module 1 handout, Section 8.1, Section 9.4.

What about overheads?

- We learned in Lecture 10 that it is inefficient to create async tasks that do little work
- In the Iterative Averaging example, each async task (forasync iteration) performs only a few operations
  - — myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
- The "seq" clause doesn't help in this case because it will just sequentialize the entire forasync loop
- An alternate approach is "loop chunking"
  - —e.g., replace

```
forasync(point[i] : [0:99]) BODY(i); // 100 tasks
```

  - —by

```
forasync(point[ii] : [0:3]) // 4 tasks
  // Each task executes a "chunk" of 25 iterations
  for (point[i] : [25*ii:25*(ii+1)-1]) BODY(i);
```

Chunking a 1-dimensional forasync loop (General approach)

- **Assume that the forasync loop originally iterates over region r**

```
forasync(point[i] : r)
  BODY(i); // No. of tasks = r.size()
```

- **Assume that we have a parameter, nc, for the desired number of chunks (tasks)**
  - —A good choice is nc = Runtime.getNumOfWorkers(), as in Listing 31
- **Assume that we have a helper method, getChunk(r, nc, ii) that returns the iteration range for chunk # ii as an HJ region**
  - —e.g., getChunk([0:99], 4, 0) = [0:24] and getChunk([0:99], 4, 3) = [75:99]
  - —No requirement for nc to evenly divide r.size()
- **The original forasync above can then be rewritten as**

```
forasync(point[ii] : [0:nc-1])
  for(point[i] : getChunk(r,nc,ii))
    BODY(i); // No. of tasks = nc
```

Implementation of getChunk() helper method in HJ

```
static region getChunk(region r, int nc, int ii) {
  // Assume that r is a 1D region
  int rLo = r.rank(0).low(); int rHi = r.rank(0).high();
  if (rLo > rHi) return [0:-1]; // Empty region
  assert(nc > 0); // nc must be > 0
  assert(0 <= ii && ii < nc); // ii must be in [0:nc-1]
  int chunkSize = ceilDiv(rHi-rLo+1, nc);
  int myLo = rLo +  ii*chunkSize;
  int myHi = Math.min(rHi, rLo + (ii+1)*chunkSize - 1);
  region retVal = [myLo:myHi];
  return retVal;
 }

static int ceilDiv(int n, int d) {
   assert(n>=0 && d>0); return (n+d-1)/ d;
 }
```

Example: HJ code for One-Dimensional Iterative Averaging with chunked for-finish-forasync-for structure

```
int nc = Runtime.getNumOfWorkers();
for (point [iter] : [0:m-1]) {
  // Compute MyNew as function of input array MyVal
  finish forasync (point [jj] : [0:nc-1]) {
    for(point [j] : getChunk([1:n],nc,jj))
      myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;
  } // finish forasync
  temp=myVal; myVal=myNew; myNew=temp;// Swap myVal & myNew;
  // myNew becomes input array for next iteration
} // for
```

Chunking a k-dimensional forasync loop (General approach)

- **Assume that the forasync loop originally iterates over region r**

```
forasync(point p : r)
  BODY(p); // No. of tasks = r.size()
```

- **Assume that we have an int array, nc = {nc0, nc1, ...}, for the desired number of chunks in each dimension**
  - —A good choice is to choose these values such that the product of nc[0]*nc[1]*... = Runtime.getNumOfWorkers()
- **Assume that we have a helper method, getChunk(r, nc, pp) that returns the iteration range for chunk pp as an HJ region**
  - —e.g., getChunk([0:99,0:99], {2,2}, [0,0]) = [0:49,0:49]
- **The original forasync above can then be rewritten as**

```
forasync(point pp : [0:nc[0]-1,0:nc[1]-1,...])
  for(point p : getChunk(r,nc,pp))
    BODY(p);
```

Worksheet #11: One-dimensional Iterative Averaging Example

Name 1: ______________________ Name 2: ______________________

1) Assuming n=9 and the input array below, perform one iteration of the iterative averaging example by only filling in the blanks for odd values of j in the myNew[] array. Recall that the computation is "myNew[j] = (myVal[j-1] + myVal[j+1])/2.0;"

index, j	0	1	2	3	4	5	6	7	8	9	10
myVal	0	0	0.2	0	0.4	0	0.6	0	0.8	0	1
myNew	0		0.2		0.4		0.6		0.8		1

2) Will the contents of myVal[] and myNew[] change in further iterations, after myNew above in 1) becomes myVal[] in the next iteration?