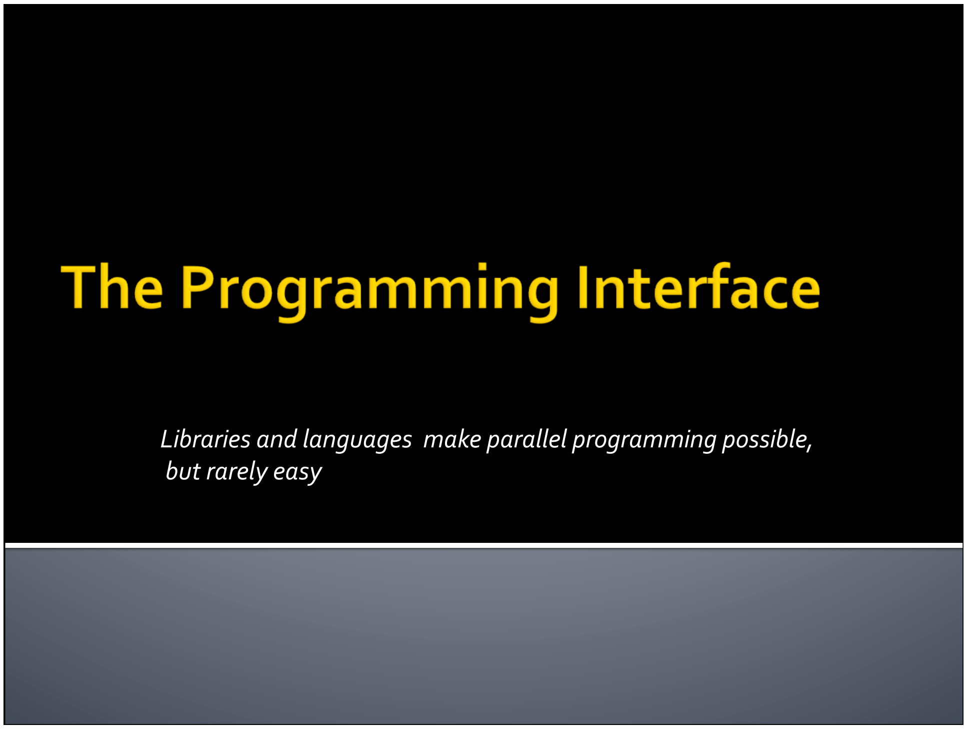
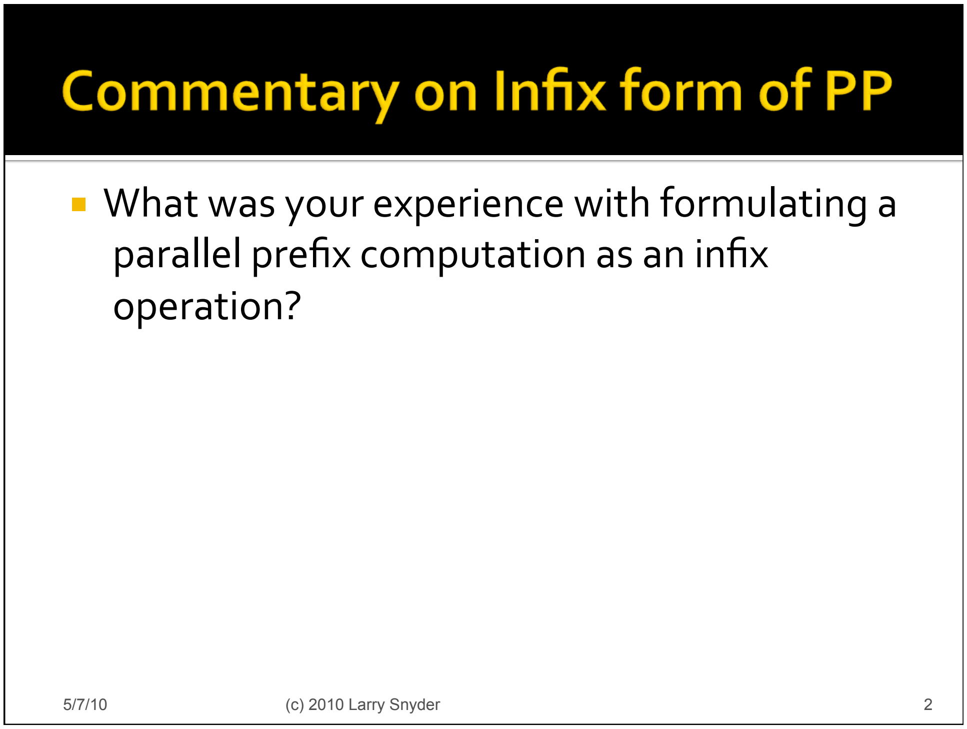


The Programming Interface

Libraries and languages make parallel programming possible, but rarely easy



Commentary on Infix form of PP

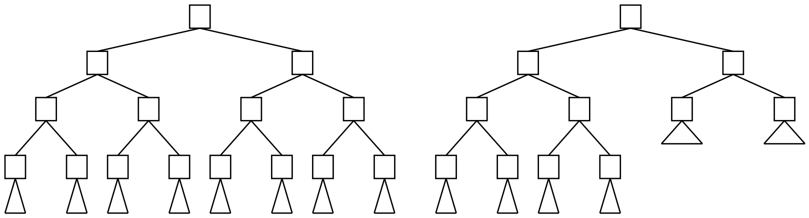
- What was your experience with formulating a parallel prefix computation as an infix operation?

From last time: Tree Algorithms

- Trees are an important component of computing
  - The "Schwartz tree" has been logical
  - Trees as data structures are complicated because they are typically more dynamic
  - Pointers are generally not available
  - Work well with work queue approach
  - As usual, we try to exploit locality and minimize communication

Breadth-first Trees

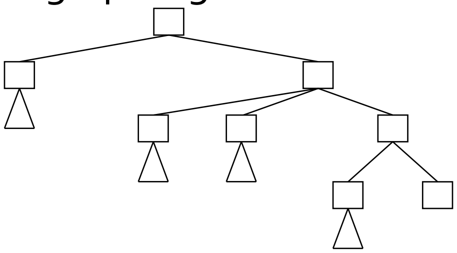
- Common in games, searching, etc



- Split: Pass 1/2 to other processor, continue
  - Stop when processors exhausted
  - Responsible for tree that remains
  - Ideal when work is localized

Depth-first

- Common in graph algorithms



- Get descendants, take one and assign others to the task queue

Key issue is managing the algorithm's progress

Coordination Among Nodes

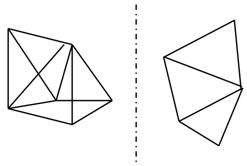
- Tree algorithms often need to know how others are progressing
  - Interrupt works if it is just a search: Eureka!!
  - Record α-β cut-offs in global variable
  - Other pruning data, e.g. best so far, also global
  - Classic error is to consult global too frequently
- Rethink: What is tree data structure's role?

Write essay: Dijkstra's algorithm is not a good… :)

Complications

- If coordination becomes too involved, consider alternate strategies:

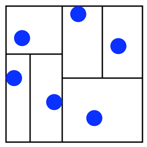
  Graph traverse => local traverse of partitioned graph



- Local computation uses sequential tree algorithms directly … stitch together

Full Enumeration

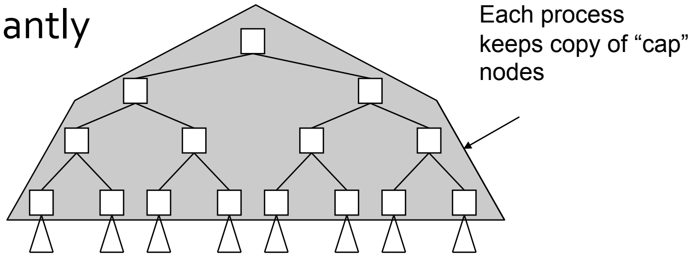
- Trees are a useful data structure for recording spatial relationships: K-D trees



- Generally, decomposition is unnecessary “all the way down” -- but this optimization implies two different regimes

Cap Reduces Communication

- The nodes near root can be stored redundantly

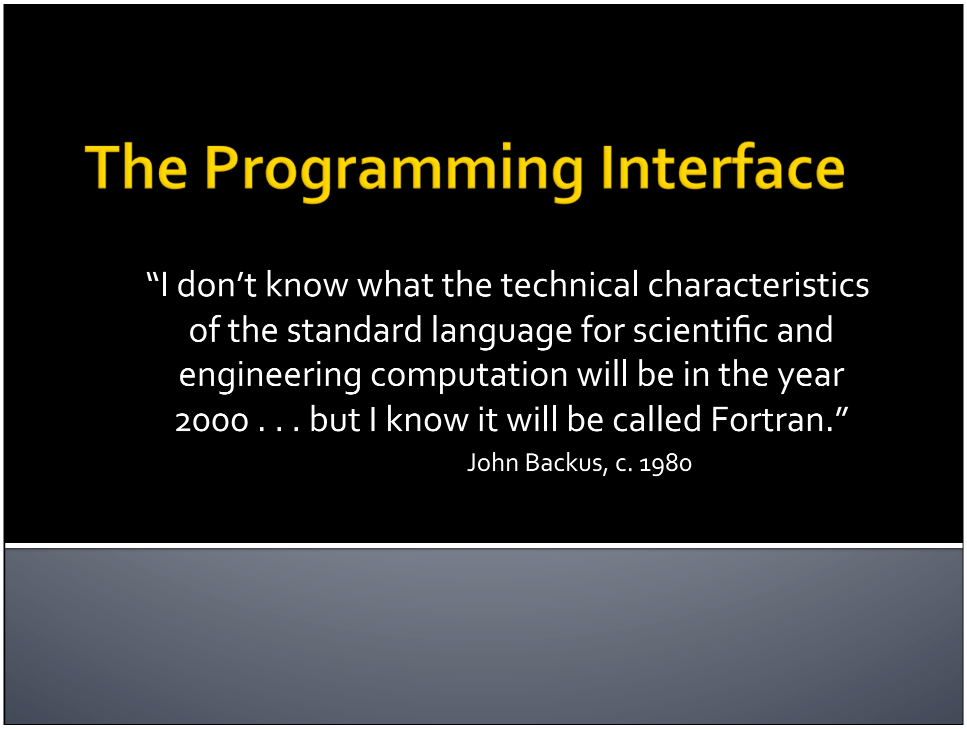


Each process keeps copy of “cap” nodes

  - Processors consult local copy -- alert others to changes

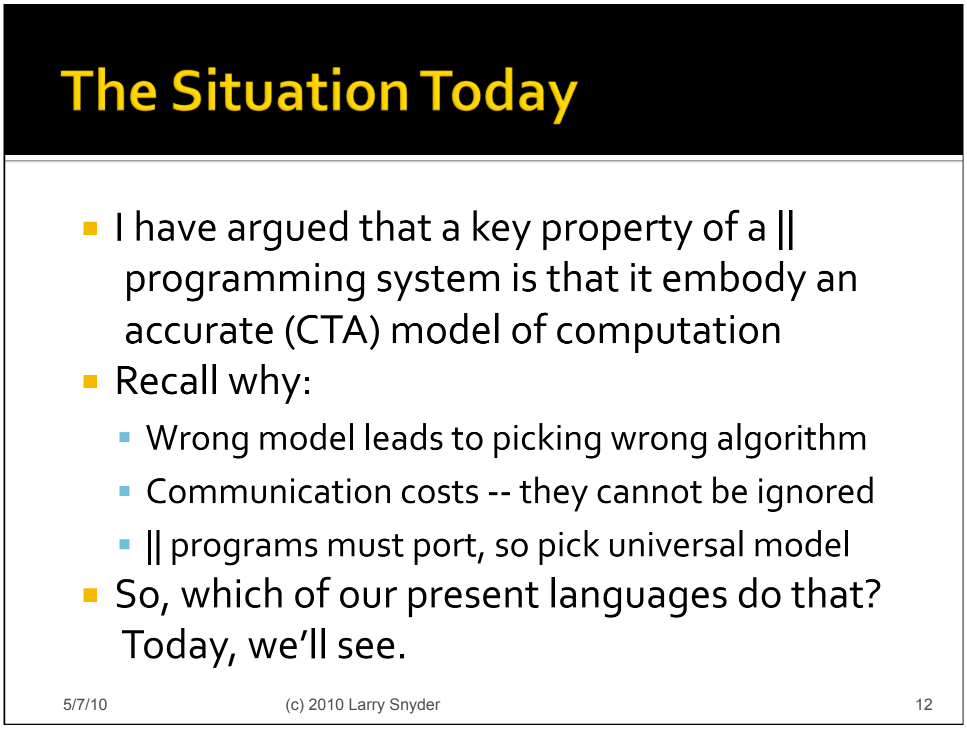
Summary of Parallel Algorithms

- Reconceptualizing is often most effective
- Focus has not been on ||ism, but on other stuff
  - Exploiting locality
  - Balancing work
  - Reducing inter-thread dependences
- We produced general purpose solution mechanisms: UD-reduce and UD-scan
- We like trees, but recognize that direct application is not likely



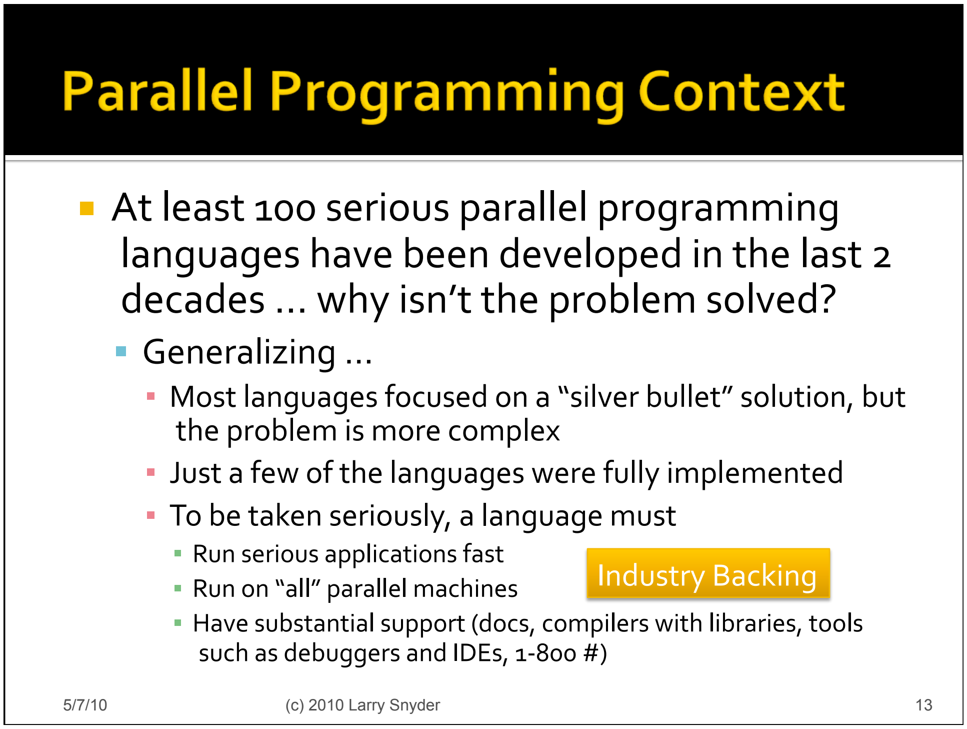
The Programming Interface

> "I don't know what the technical characteristics of the standard language for scientific and engineering computation will be in the year 2000 . . . but I know it will be called Fortran."
>
> John Backus, c. 1980



The Situation Today

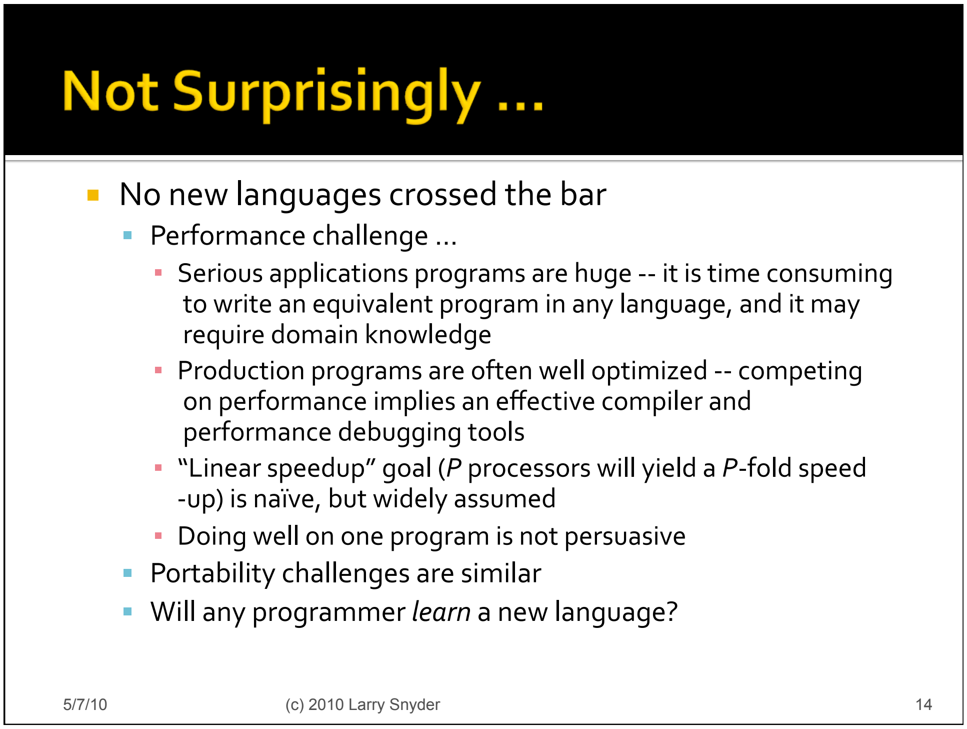
- I have argued that a key property of a || programming system is that it embody an accurate (CTA) model of computation
- Recall why:
  - Wrong model leads to picking wrong algorithm
  - Communication costs -- they cannot be ignored
  - || programs must port, so pick universal model
- So, which of our present languages do that? Today, we'll see.



Parallel Programming Context

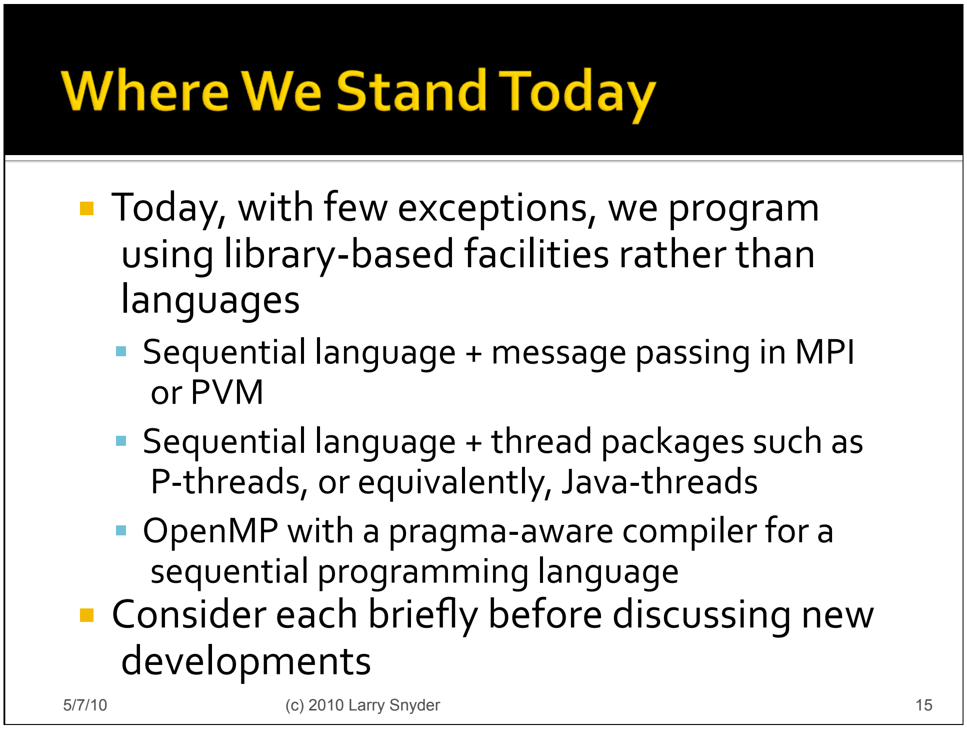
- At least 100 serious parallel programming languages have been developed in the last 2 decades … why isn't the problem solved?
  - Generalizing …
    - Most languages focused on a "silver bullet" solution, but the problem is more complex
    - Just a few of the languages were fully implemented
    - To be taken seriously, a language must
      - Run serious applications fast
      - Run on "all" parallel machines
      - Have substantial support (docs, compilers with libraries, tools such as debuggers and IDEs, 1-800 #)

Industry Backing



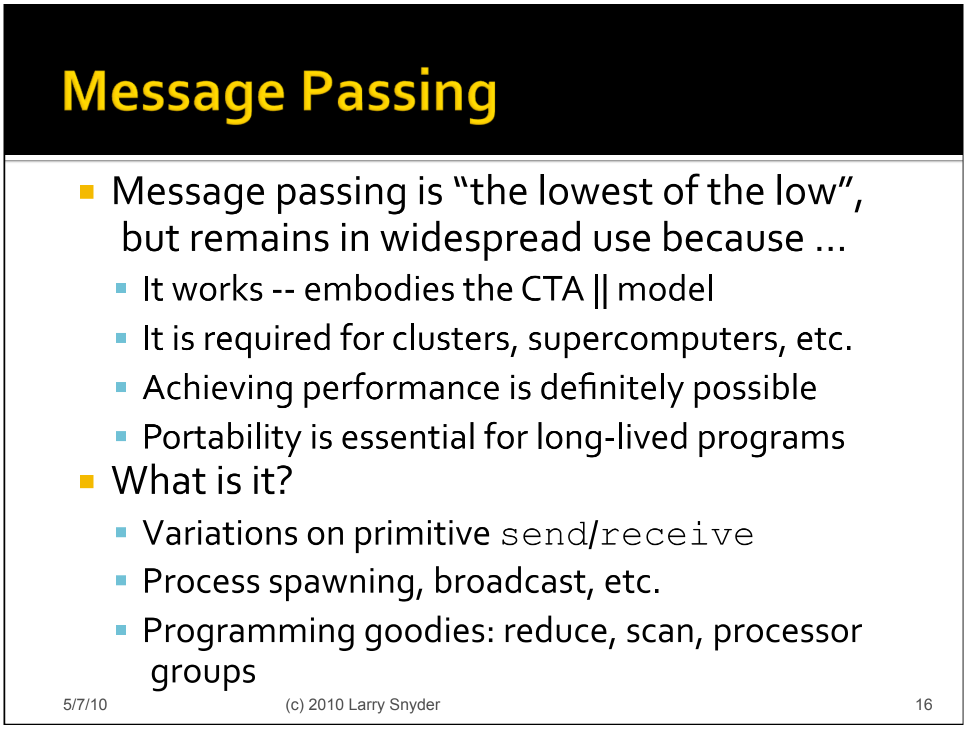
Not Surprisingly …

- No new languages crossed the bar
  - Performance challenge …
    - Serious applications programs are huge -- it is time consuming to write an equivalent program in any language, and it may require domain knowledge
    - Production programs are often well optimized -- competing on performance implies an effective compiler and performance debugging tools
    - "Linear speedup" goal (*P* processors will yield a *P*-fold speed -up) is naïve, but widely assumed
    - Doing well on one program is not persuasive
  - Portability challenges are similar
  - Will any programmer *learn* a new language?



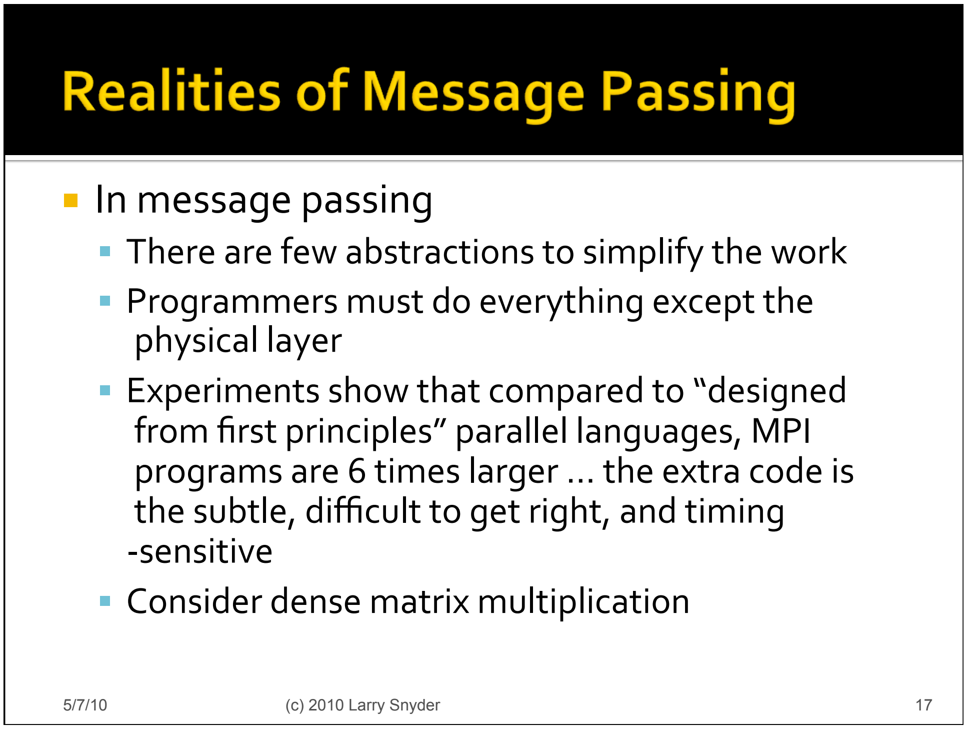
Where We Stand Today

- Today, with few exceptions, we program using library-based facilities rather than languages
  - Sequential language + message passing in MPI or PVM
  - Sequential language + thread packages such as P-threads, or equivalently, Java-threads
  - OpenMP with a pragma-aware compiler for a sequential programming language
- Consider each briefly before discussing new developments



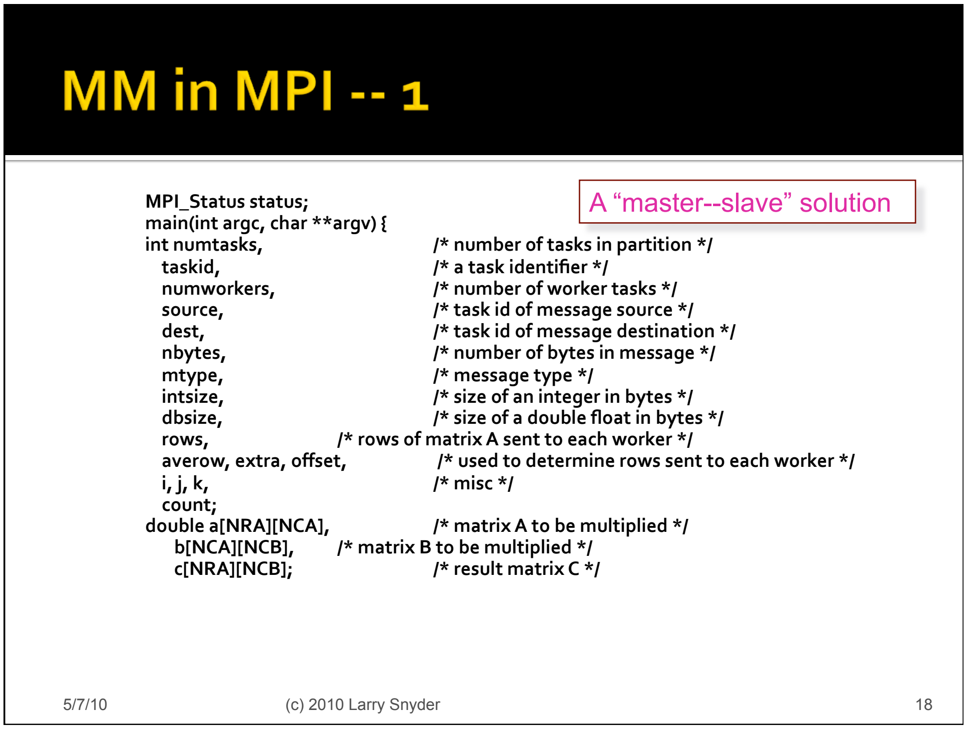
Message Passing

- Message passing is “the lowest of the low”, but remains in widespread use because …
  - It works -- embodies the CTA || model
  - It is required for clusters, supercomputers, etc.
  - Achieving performance is definitely possible
  - Portability is essential for long-lived programs
- What is it?
  - Variations on primitive `send`/`receive`
  - Process spawning, broadcast, etc.
  - Programming goodies: reduce, scan, processor groups



Realities of Message Passing

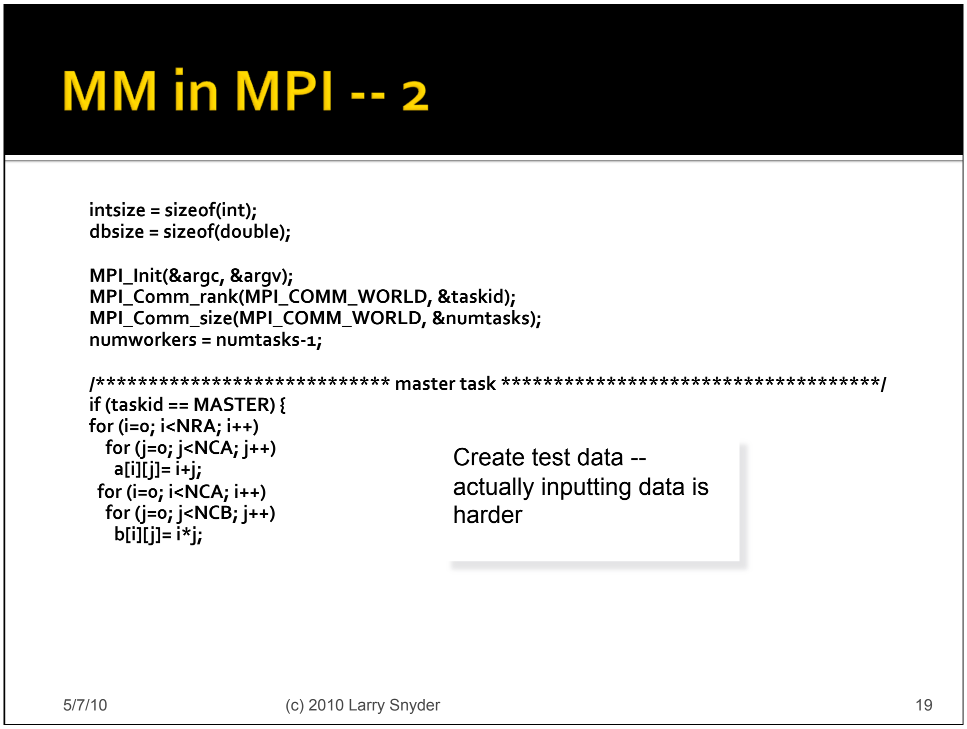
- In message passing
  - There are few abstractions to simplify the work
  - Programmers must do everything except the physical layer
  - Experiments show that compared to “designed from first principles” parallel languages, MPI programs are 6 times larger … the extra code is the subtle, difficult to get right, and timing -sensitive
  - Consider dense matrix multiplication



MM in MPI -- 1

A “master--slave” solution

```
MPI_Status status;
main(int argc, char **argv) {
int numtasks,                    /* number of tasks in partition */
   taskid,                       /* a task identifier */
   numworkers,                   /* number of worker tasks */
   source,                       /* task id of message source */
   dest,                         /* task id of message destination */
   nbytes,                       /* number of bytes in message */
   mtype,                        /* message type */
   intsize,                      /* size of an integer in bytes */
   dbsize,                       /* size of a double float in bytes */
   rows,               /* rows of matrix A sent to each worker */
   averow, extra, offset,         /* used to determine rows sent to each worker */
   i, j, k,                      /* misc */
   count;
double a[NRA][NCA],              /* matrix A to be multiplied */
     b[NCA][NCB],      /* matrix B to be multiplied */
     c[NRA][NCB];                /* result matrix C */
```



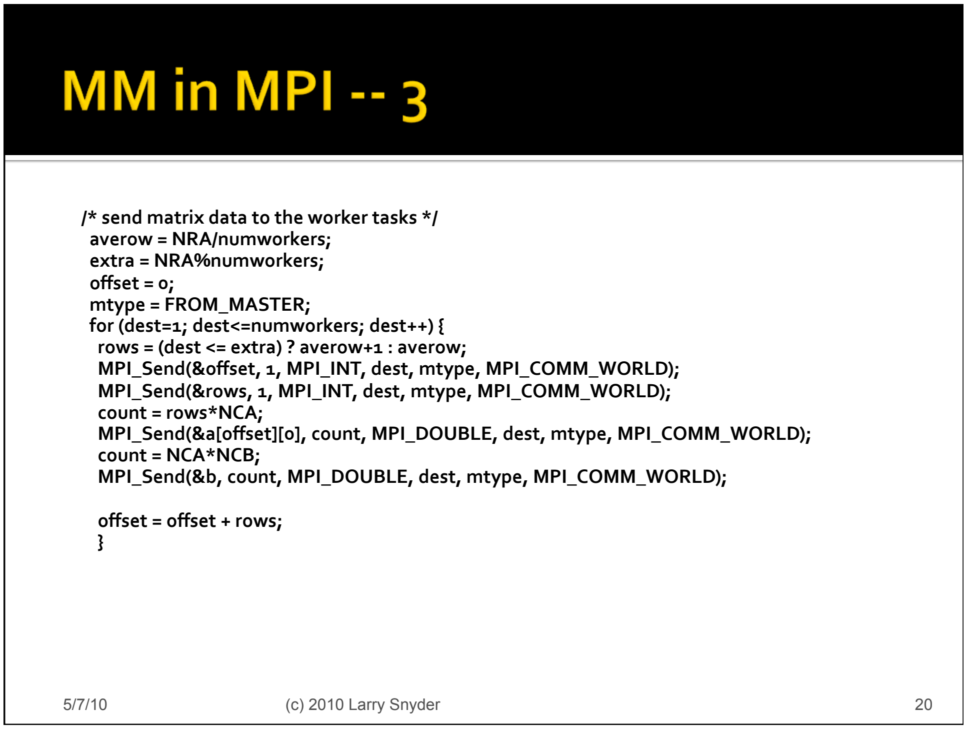
MM in MPI -- 2

```
intsize = sizeof(int);
dbsize = sizeof(double);

MPI_Init(&argc, &argv);
MPI_Comm_rank(MPI_COMM_WORLD, &taskid);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
numworkers = numtasks-1;

/*************************** master task ************************************/
if (taskid == MASTER) {
for (i=0; i<NRA; i++)
  for (j=0; j<NCA; j++)
    a[i][j]= i+j;
 for (i=0; i<NCA; i++)
  for (j=0; j<NCB; j++)
    b[i][j]= i*j;
```

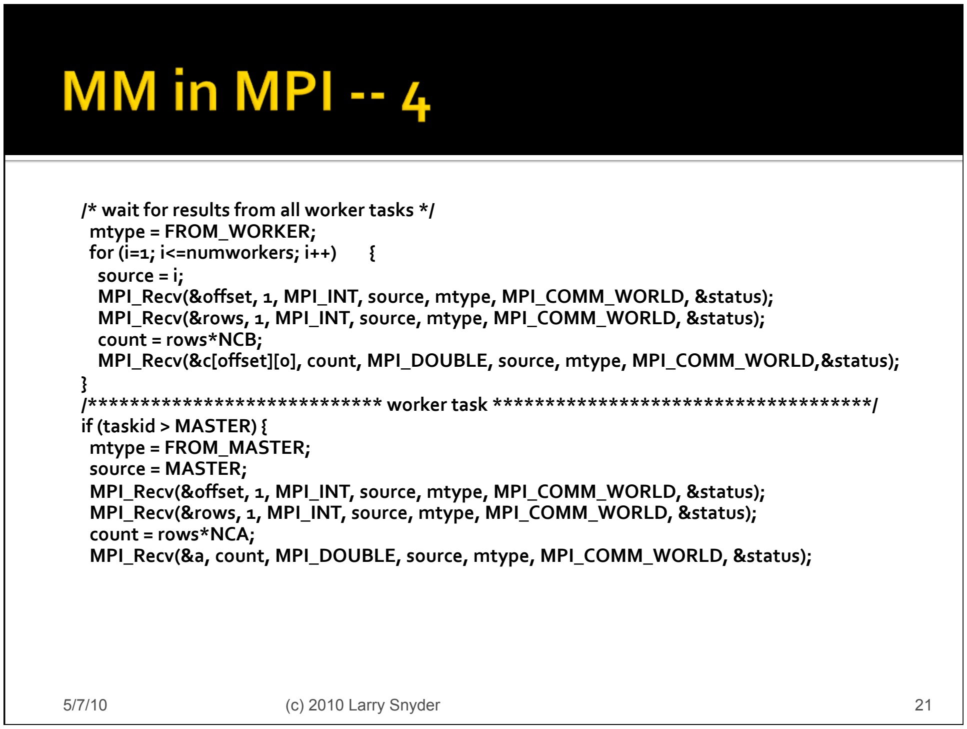
Create test data -- actually inputting data is harder



MM in MPI -- 3

```
/* send matrix data to the worker tasks */
 averow = NRA/numworkers;
 extra = NRA%numworkers;
 offset = 0;
 mtype = FROM_MASTER;
 for (dest=1; dest<=numworkers; dest++) {
   rows = (dest <= extra) ? averow+1 : averow;
   MPI_Send(&offset, 1, MPI_INT, dest, mtype, MPI_COMM_WORLD);
   MPI_Send(&rows, 1, MPI_INT, dest, mtype, MPI_COMM_WORLD);
   count = rows*NCA;
   MPI_Send(&a[offset][0], count, MPI_DOUBLE, dest, mtype, MPI_COMM_WORLD);
   count = NCA*NCB;
   MPI_Send(&b, count, MPI_DOUBLE, dest, mtype, MPI_COMM_WORLD);

   offset = offset + rows;
   }
```



MM in MPI -- 4

```
/* wait for results from all worker tasks */
 mtype = FROM_WORKER;
 for (i=1; i<=numworkers; i++)      {
   source = i;
   MPI_Recv(&offset, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
   MPI_Recv(&rows, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
   count = rows*NCB;
   MPI_Recv(&c[offset][0], count, MPI_DOUBLE, source, mtype, MPI_COMM_WORLD,&status);
}
/*************************** worker task ***********************************/
if (taskid > MASTER) {
 mtype = FROM_MASTER;
 source = MASTER;
 MPI_Recv(&offset, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
 MPI_Recv(&rows, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
 count = rows*NCA;
 MPI_Recv(&a, count, MPI_DOUBLE, source, mtype, MPI_COMM_WORLD, &status);
```

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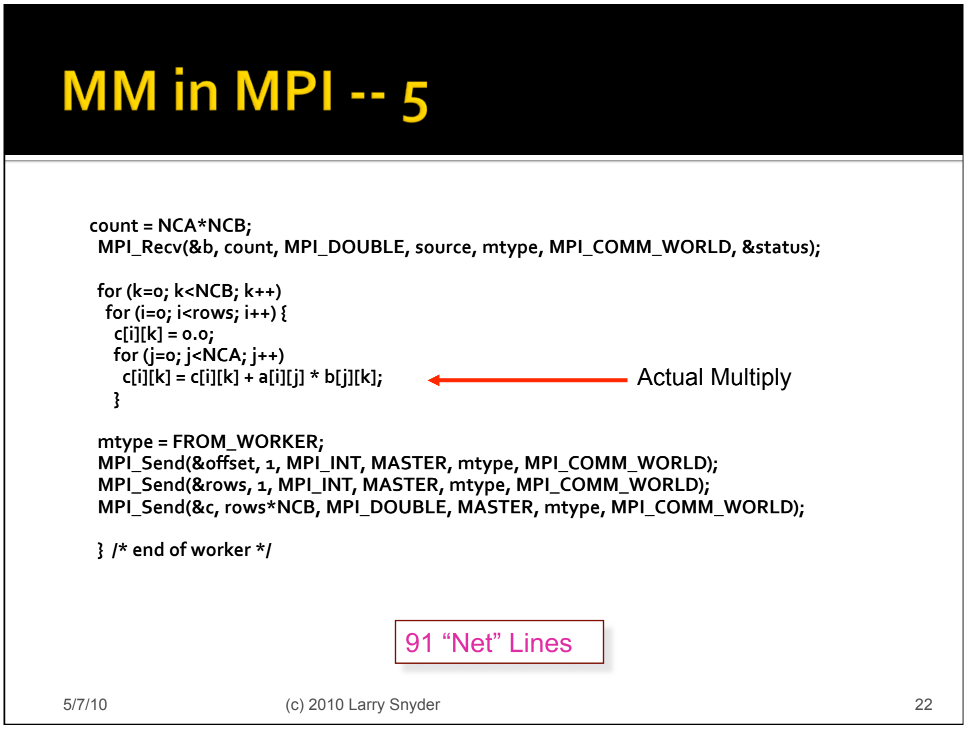

MM in MPI -- 5

```
 count = NCA*NCB;
   MPI_Recv(&b, count, MPI_DOUBLE, source, mtype, MPI_COMM_WORLD, &status);

   for (k=0; k<NCB; k++)
     for (i=0; i<rows; i++) {
       c[i][k] = 0.0;
       for (j=0; j<NCA; j++)
         c[i][k] = c[i][k] + a[i][j] * b[j][k];
       }

   mtype = FROM_WORKER;
   MPI_Send(&offset, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD);
   MPI_Send(&rows, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD);
   MPI_Send(&c, rows*NCB, MPI_DOUBLE, MASTER, mtype, MPI_COMM_WORLD);

   } /* end of worker */
```

Actual Multiply

91 “Net” Lines

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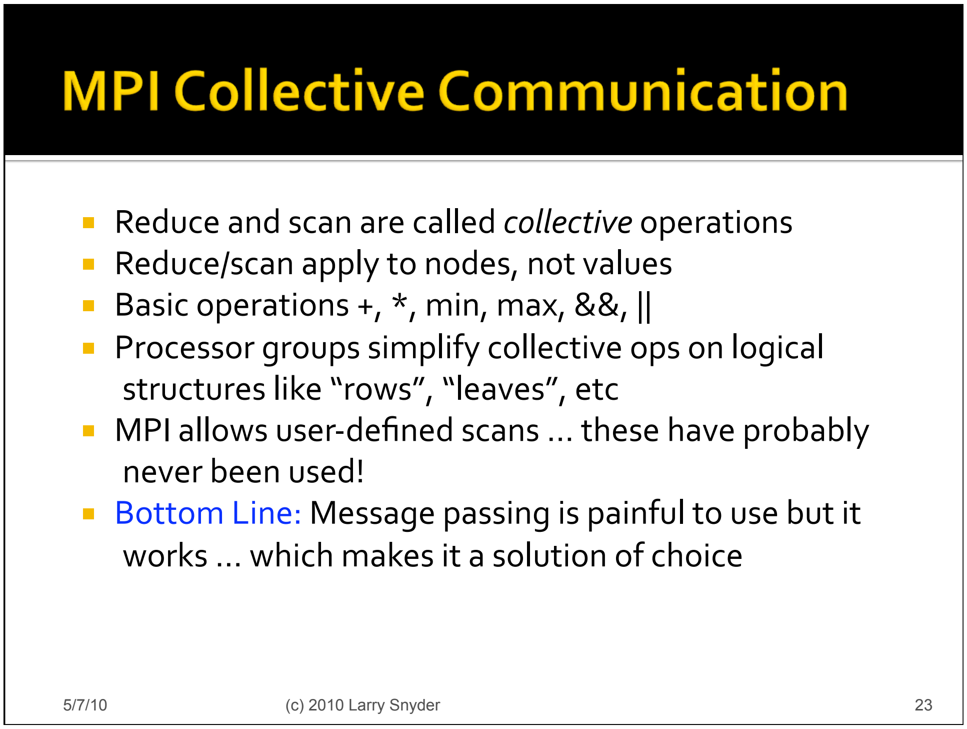
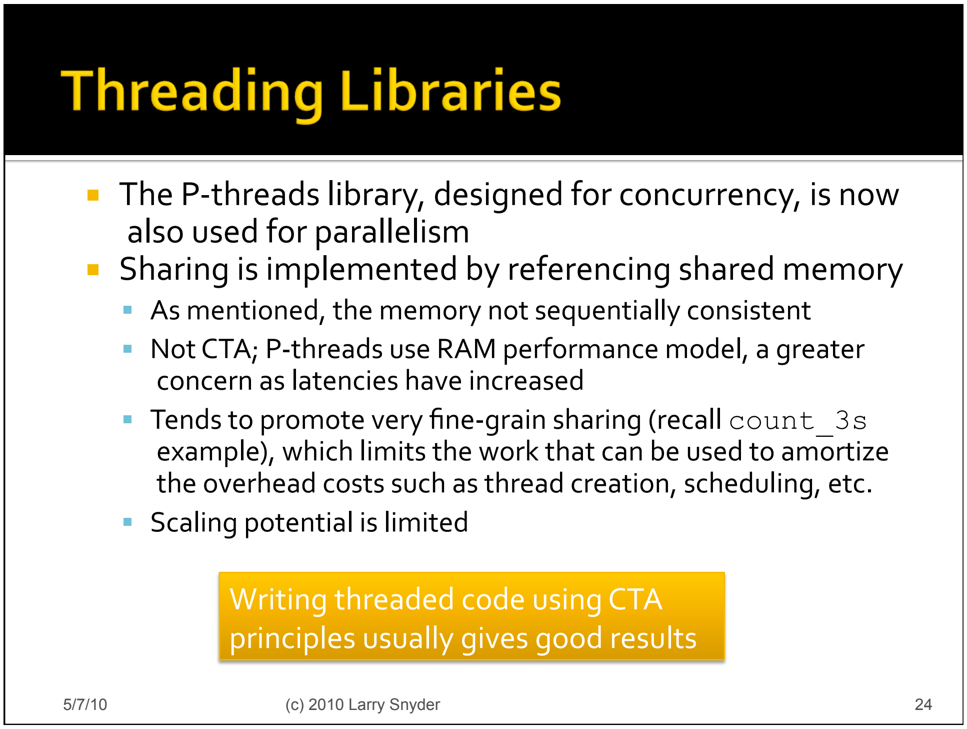


MPI Collective Communication

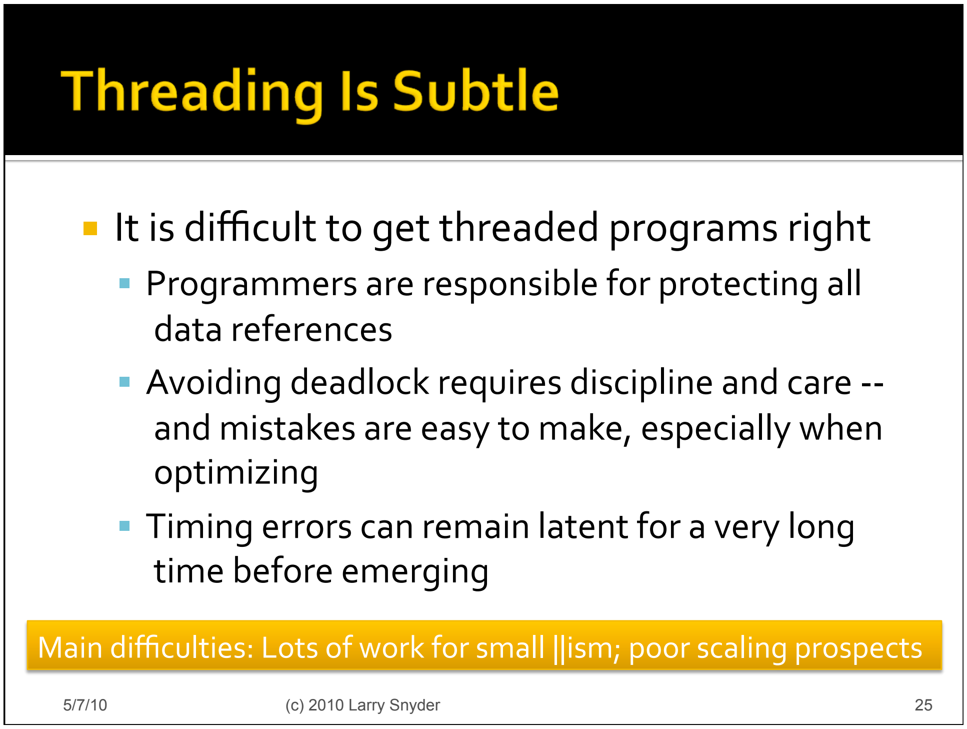
- Reduce and scan are called *collective* operations
- Reduce/scan apply to nodes, not values
- Basic operations +, *, min, max, &&, ||
- Processor groups simplify collective ops on logical structures like "rows", "leaves", etc
- MPI allows user-defined scans … these have probably never been used!
- Bottom Line: Message passing is painful to use but it works … which makes it a solution of choice



Threading Libraries

- The P-threads library, designed for concurrency, is now also used for parallelism
- Sharing is implemented by referencing shared memory
  - As mentioned, the memory not sequentially consistent
  - Not CTA; P-threads use RAM performance model, a greater concern as latencies have increased
  - Tends to promote very fine-grain sharing (recall `count_3s` example), which limits the work that can be used to amortize the overhead costs such as thread creation, scheduling, etc.
  - Scaling potential is limited

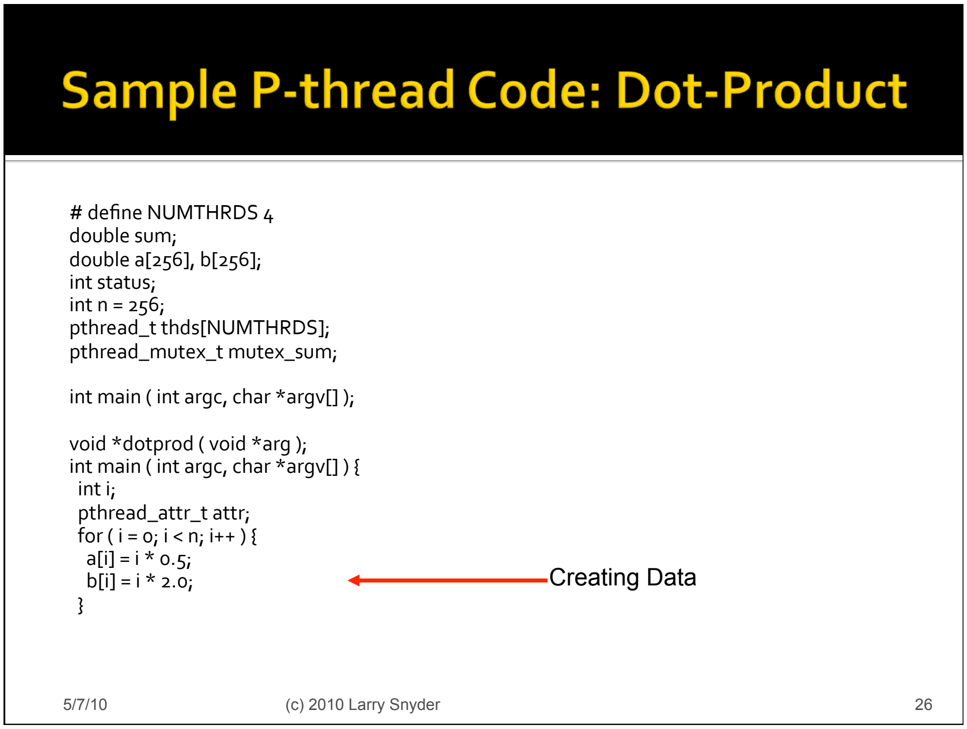
Writing threaded code using CTA principles usually gives good results



Threading Is Subtle

- It is difficult to get threaded programs right
  - Programmers are responsible for protecting all data references
  - Avoiding deadlock requires discipline and care -- and mistakes are easy to make, especially when optimizing
  - Timing errors can remain latent for a very long time before emerging

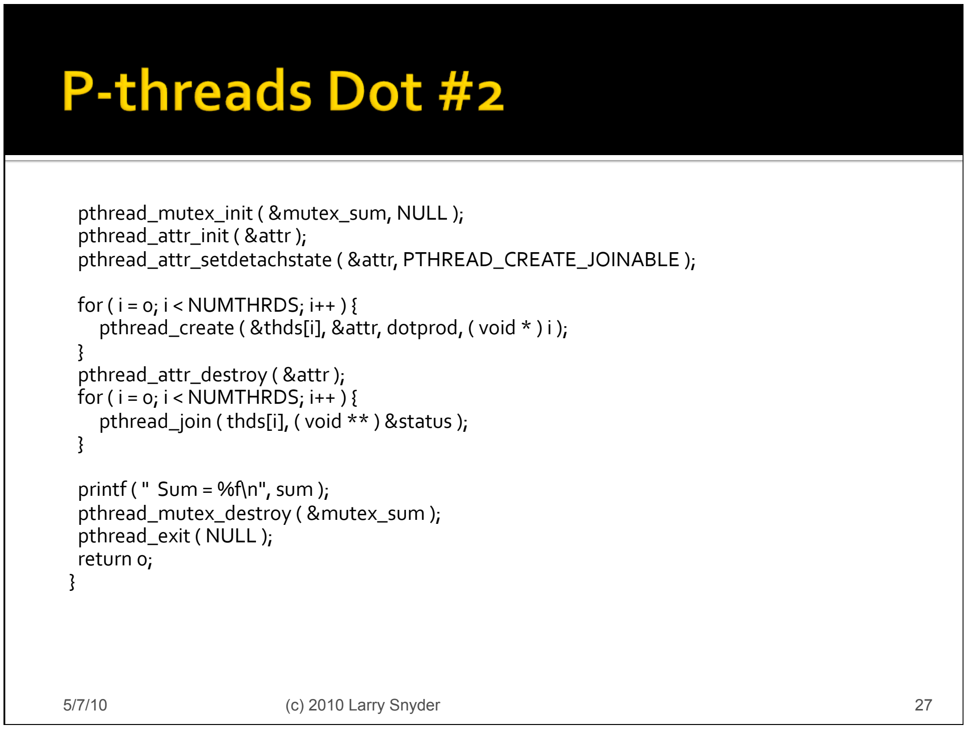
Main difficulties: Lots of work for small ||ism; poor scaling prospects



Sample P-thread Code: Dot-Product

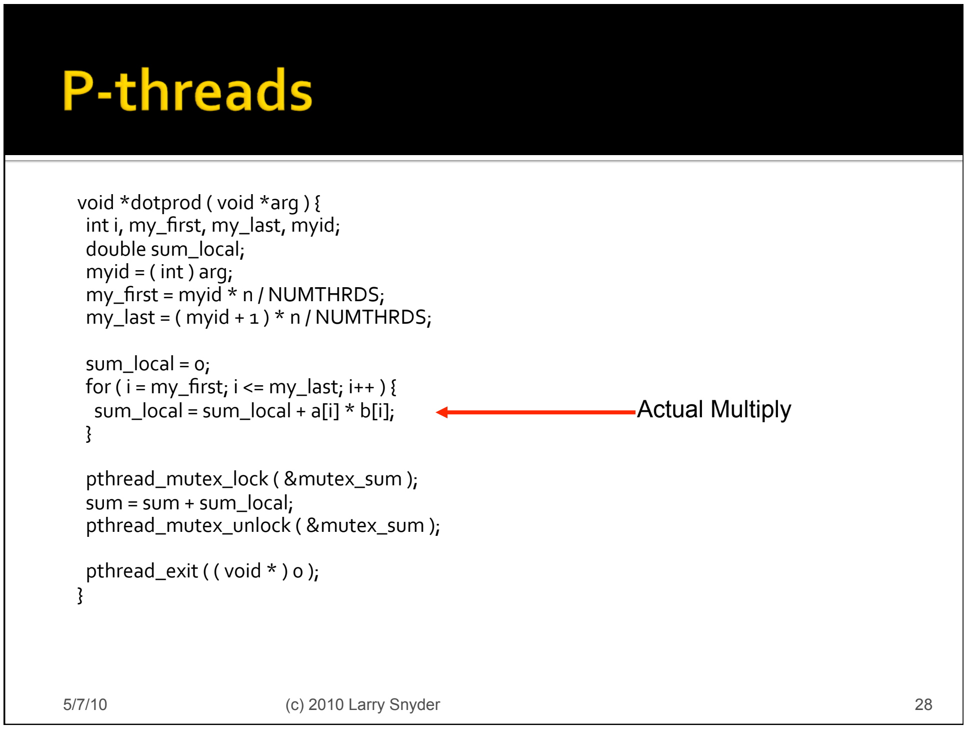
```
# define NUMTHRDS 4
double sum;
double a[256], b[256];
int status;
int n = 256;
pthread_t thds[NUMTHRDS];
pthread_mutex_t mutex_sum;

int main ( int argc, char *argv[] );

void *dotprod ( void *arg );
int main ( int argc, char *argv[] ) {
 int i;
 pthread_attr_t attr;
 for ( i = 0; i < n; i++ ) {
  a[i] = i * 0.5;
  b[i] = i * 2.0;
 }
```

Creating Data



P-threads Dot #2

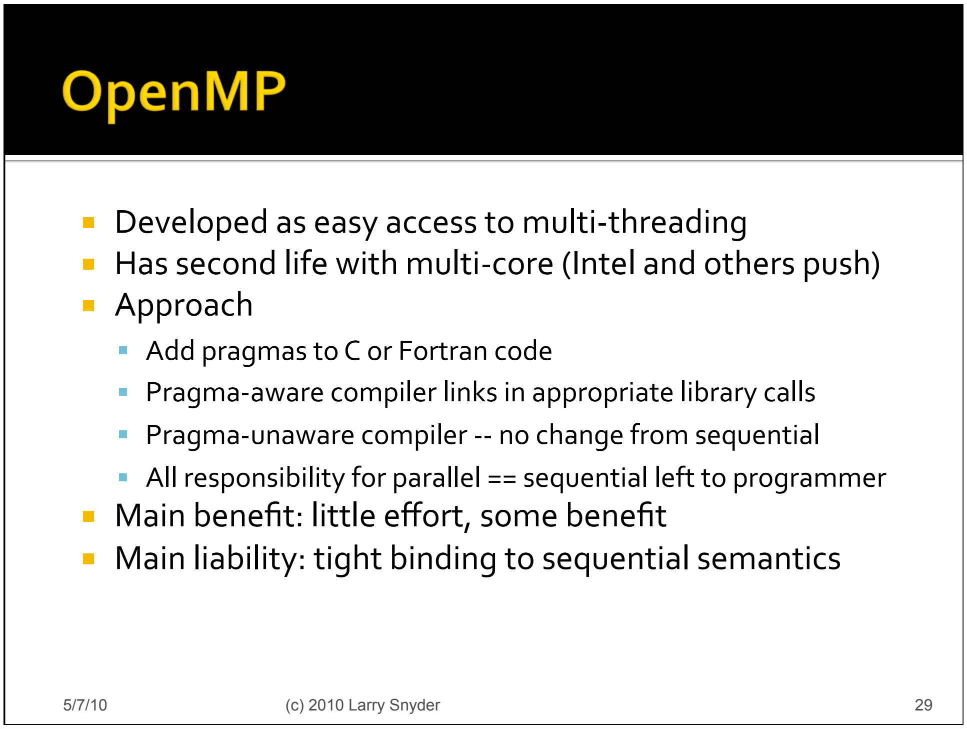
```
  pthread_mutex_init ( &mutex_sum, NULL );
  pthread_attr_init ( &attr );
  pthread_attr_setdetachstate ( &attr, PTHREAD_CREATE_JOINABLE );

  for ( i = 0; i < NUMTHRDS; i++ ) {
     pthread_create ( &thds[i], &attr, dotprod, ( void * ) i );
  }
  pthread_attr_destroy ( &attr );
  for ( i = 0; i < NUMTHRDS; i++ ) {
     pthread_join ( thds[i], ( void ** ) &status );
  }

  printf ( "  Sum = %f\n", sum );
  pthread_mutex_destroy ( &mutex_sum );
  pthread_exit ( NULL );
  return 0;
}
```



P-threads

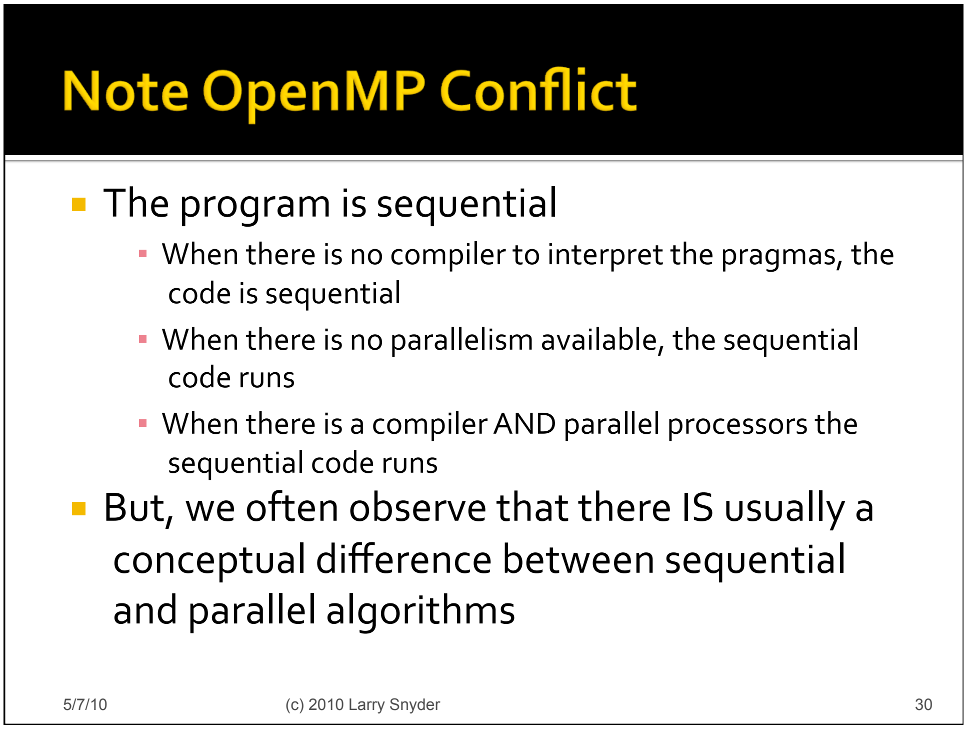
```
void *dotprod ( void *arg ) {
 int i, my_first, my_last, myid;
 double sum_local;
 myid = ( int ) arg;
 my_first = myid * n / NUMTHRDS;
 my_last = ( myid + 1 ) * n / NUMTHRDS;

 sum_local = 0;
 for ( i = my_first; i <= my_last; i++ ) {
  sum_local = sum_local + a[i] * b[i];
 }

 pthread_mutex_lock ( &mutex_sum );
 sum = sum + sum_local;
 pthread_mutex_unlock ( &mutex_sum );

 pthread_exit ( ( void * ) 0 );
}
```

Actual Multiply



OpenMP

- Developed as easy access to multi-threading
- Has second life with multi-core (Intel and others push)
- Approach
  - Add pragmas to C or Fortran code
  - Pragma-aware compiler links in appropriate library calls
  - Pragma-unaware compiler -- no change from sequential
  - All responsibility for parallel == sequential left to programmer
- Main benefit: little effort, some benefit
- Main liability: tight binding to sequential semantics



Note OpenMP Conflict

- The program is sequential
  - When there is no compiler to interpret the pragmas, the code is sequential
  - When there is no parallelism available, the sequential code runs
  - When there is a compiler AND parallel processors the sequential code runs
- But, we often observe that there IS usually a conceptual difference between sequential and parallel algorithms

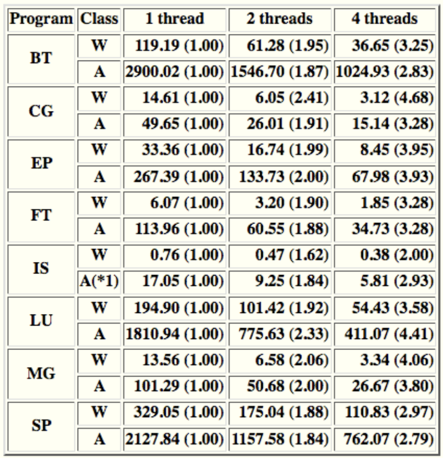
Sample Code -- Dot Product

```
double dotProduct()  {
    int I; double sum_p;
    double result = 0;
    #pragma omp parallel shared(a, b, result) private(sum_p)
    {
      sum_p=0;
    #pragma omp parallel for private(i)
      for(i=0; i<n; i++) {
          sum_p += a[i]*b[i];
       }
     #pragma omp critical
       {
       result += sum_p;
       }
     }
     return result;
  }
```

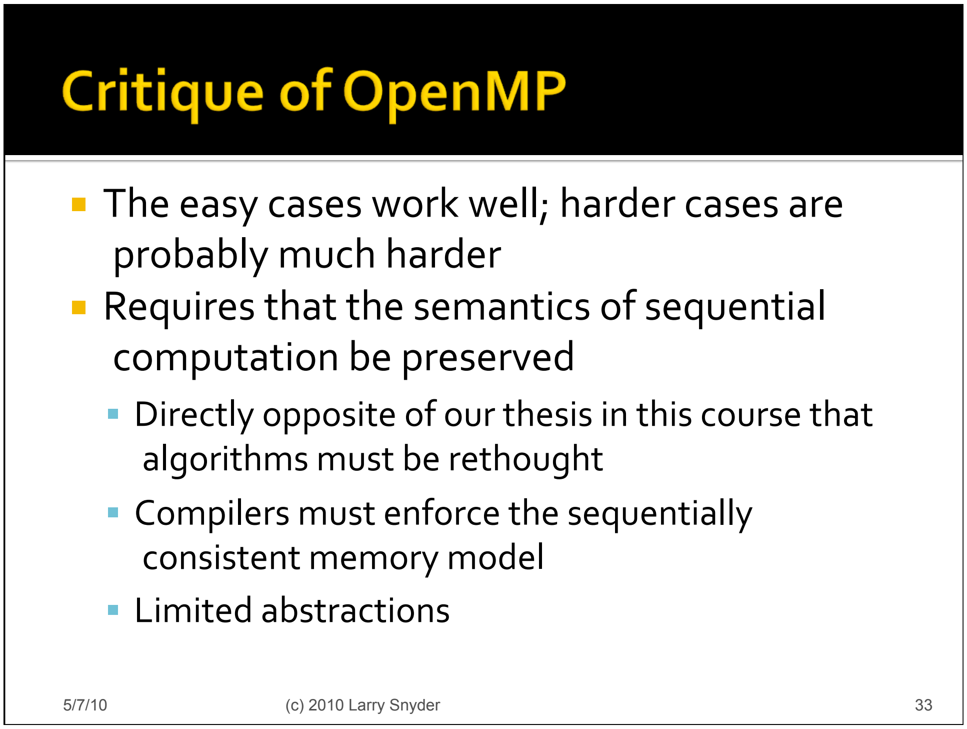
OpenMP Compiler

- 4 Processor Sun Enterprise running the NAS PB written in C with OpenMP

Block Tridiagonal
Conjugate Gradient
Embarrassingly ||
Fast Fourier Trans
Integer Sort
LU Decomposition
Multigrid Iteration
Sparse Matrix-Vector

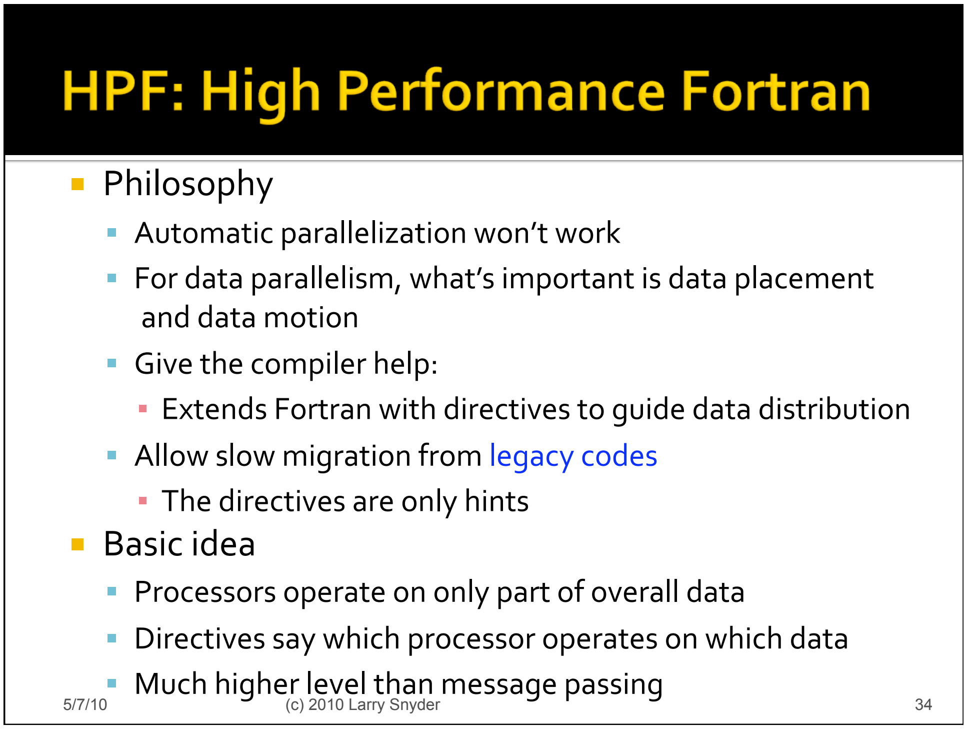


Program	Class	1 thread	2 threads	4 threads
BT	W	119.19 (1.00)	61.28 (1.95)	36.65 (3.25)
	A	2900.02 (1.00)	1546.70 (1.87)	1024.93 (2.83)
CG	W	14.61 (1.00)	6.05 (2.41)	3.12 (4.68)
	A	49.65 (1.00)	26.01 (1.91)	15.14 (3.28)
EP	W	33.36 (1.00)	16.74 (1.99)	8.45 (3.95)
	A	267.39 (1.00)	133.73 (2.00)	67.98 (3.93)
FT	W	6.07 (1.00)	3.20 (1.90)	1.85 (3.28)
	A	113.96 (1.00)	60.55 (1.88)	34.73 (3.28)
IS	W	0.76 (1.00)	0.47 (1.62)	0.38 (2.00)
	A(*1)	17.05 (1.00)	9.25 (1.84)	5.81 (2.93)
LU	W	194.90 (1.00)	101.42 (1.92)	54.43 (3.58)
	A	1810.94 (1.00)	775.63 (2.33)	411.07 (4.41)
MG	W	13.56 (1.00)	6.58 (2.06)	3.34 (4.06)
	A	101.29 (1.00)	50.68 (2.00)	26.67 (3.80)
SP	W	329.05 (1.00)	175.04 (1.88)	110.83 (2.97)
	A	2127.84 (1.00)	1157.58 (1.84)	762.07 (2.79)



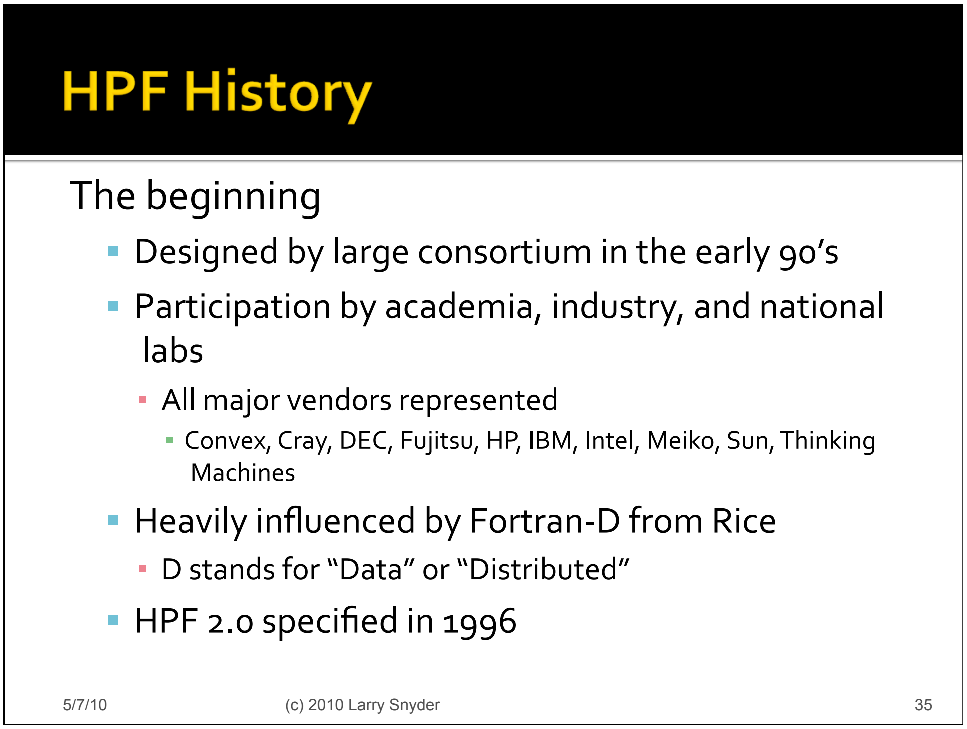
Critique of OpenMP

- The easy cases work well; harder cases are probably much harder
- Requires that the semantics of sequential computation be preserved
  - Directly opposite of our thesis in this course that algorithms must be rethought
  - Compilers must enforce the sequentially consistent memory model
  - Limited abstractions



HPF: High Performance Fortran

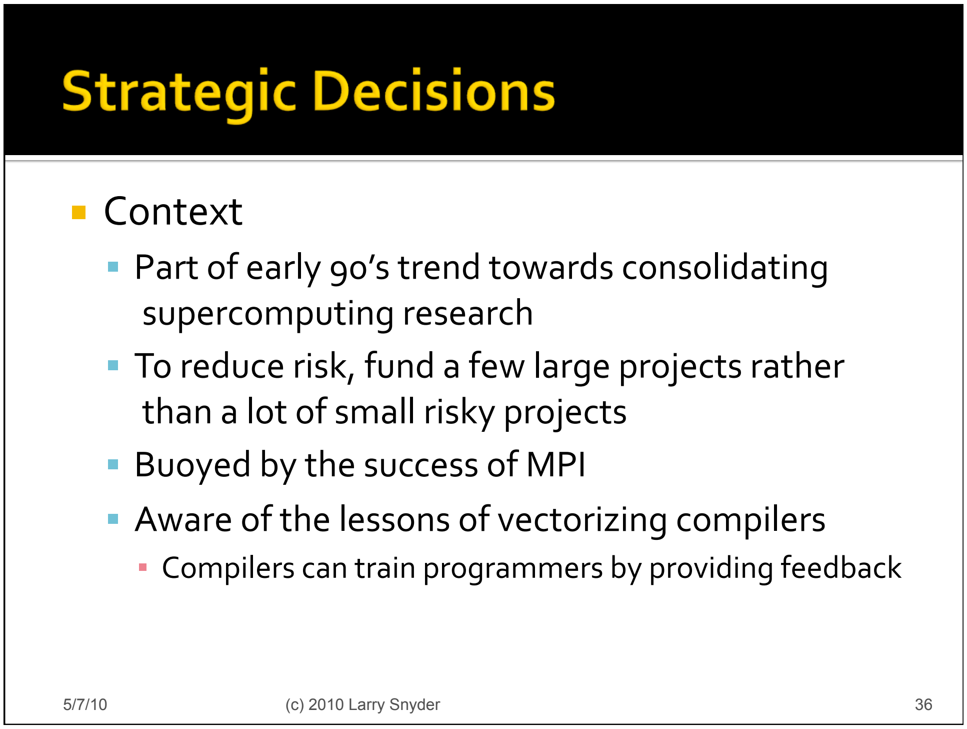
- Philosophy
  - Automatic parallelization won't work
  - For data parallelism, what's important is data placement and data motion
  - Give the compiler help:
    - Extends Fortran with directives to guide data distribution
  - Allow slow migration from legacy codes
    - The directives are only hints
- Basic idea
  - Processors operate on only part of overall data
  - Directives say which processor operates on which data
  - Much higher level than message passing



HPF History

The beginning

- Designed by large consortium in the early 90's
- Participation by academia, industry, and national labs
  - All major vendors represented
    - Convex, Cray, DEC, Fujitsu, HP, IBM, Intel, Meiko, Sun, Thinking Machines
- Heavily influenced by Fortran-D from Rice
  - D stands for "Data" or "Distributed"
- HPF 2.0 specified in 1996



Strategic Decisions

- Context
  - Part of early 90's trend towards consolidating supercomputing research
  - To reduce risk, fund a few large projects rather than a lot of small risky projects
  - Buoyed by the success of MPI
  - Aware of the lessons of vectorizing compilers
    - Compilers can train programmers by providing feedback

Vectorizing Compilers

- Basic idea
  - Instead of looping over elements of a vector, perform a single vector instruction
  - Example

```
for (i=0; i<100; i++)
    A[i] = B[i] + C[i];
```

Vector code

- Execute 4 instructions once
  - 2 vector Loads
  - 1 vector Add
  - 1 vector Store

- Scalar code
  - Execute 4 insts 100 times, 2 Loads, 1 Add, 1 Store
- Advantages?

Rules for Writing Vectorizable Code

- 1. Avoid conditionals in loops

```
for (i=0; i<100; i++)
    if (A[i] > MaxFloat)
      A[i] = MaxFloat;
```

```
for (i=0; i<100; i++)
    A[i] = min(A[i],MaxFloat)
```

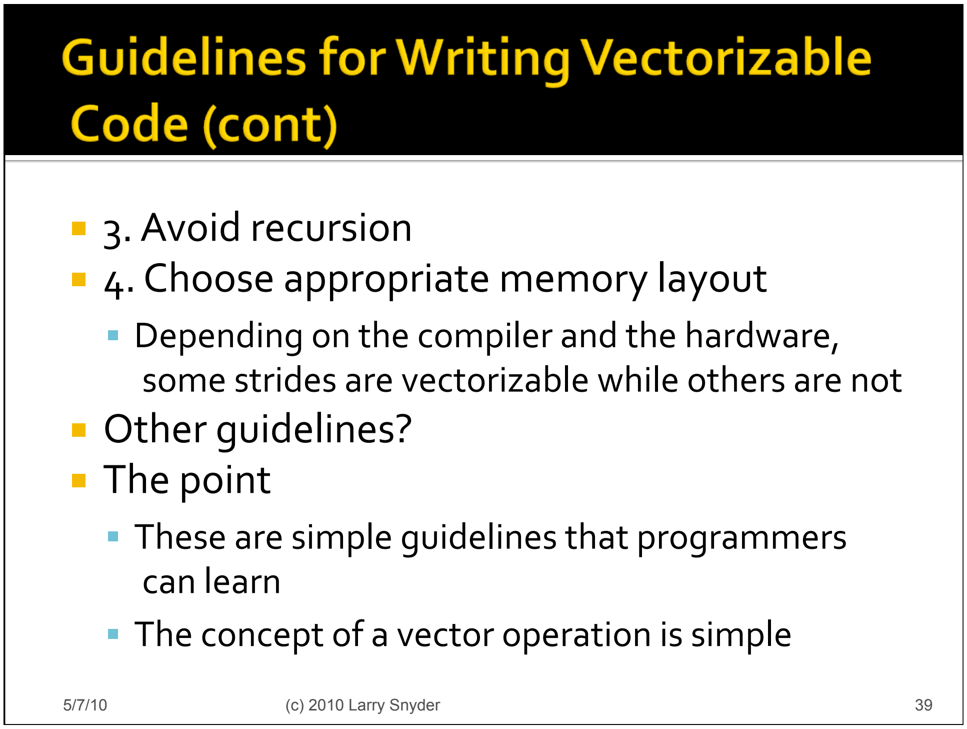
- 2. Promote scalar functions

```
for (i=0; i<100; i++)
    foo (A[i], B[i]);
```

```
Foo(A, B);
```

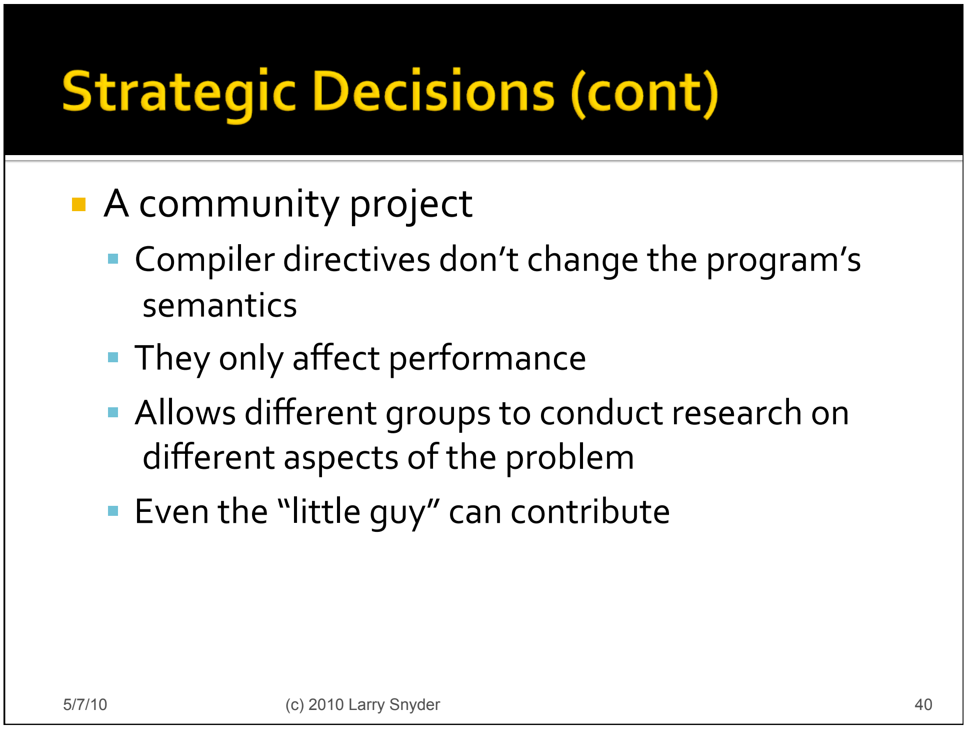
- One function call
- Body of this function call can be easily vectorized

  - Lots of function calls inside a tight loop
  - Function call boundaries inhibit vectorization



Guidelines for Writing Vectorizable Code (cont)

- 3. Avoid recursion
- 4. Choose appropriate memory layout
  - Depending on the compiler and the hardware, some strides are vectorizable while others are not
- Other guidelines?
- The point
  - These are simple guidelines that programmers can learn
  - The concept of a vector operation is simple



Strategic Decisions (cont)

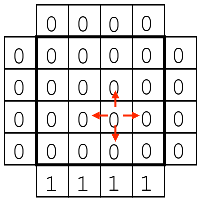
- A community project
  - Compiler directives don't change the program's semantics
  - They only affect performance
  - Allows different groups to conduct research on different aspects of the problem
  - Even the "little guy" can contribute

Fortran 90

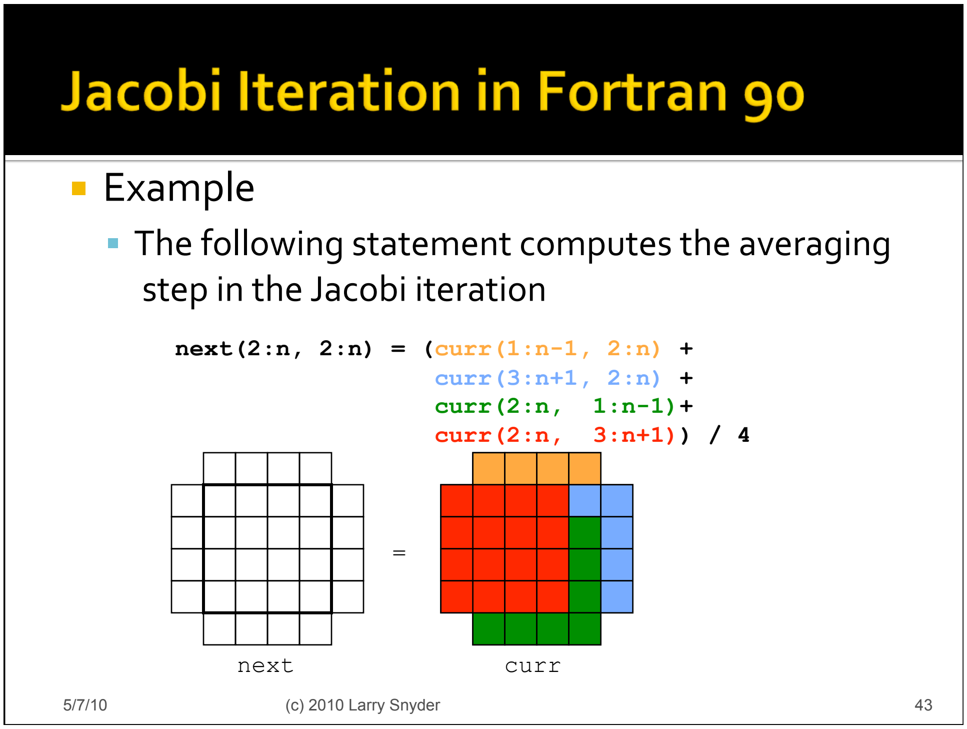
- An array language
  - Can operate with entire arrays as operands
    - Pairwise operators
    - Reduction operators
  - Uses slice notation
    - `array1d(low: high: stride)` represents the elements of `array1` starting at `low`, ending at `high`, and skipping every `stride-1` elements
    - The stride is an optional operand
  - Converts many loops into array statements

Example Computation

- Jacobi Iteration
  - The elements of an array, initialized to 0.0 except for 1.0's along its southern border, are iteratively replaced with the average of their 4 nearest neighbors until the greatest change between two iterations is less than some epsilon.



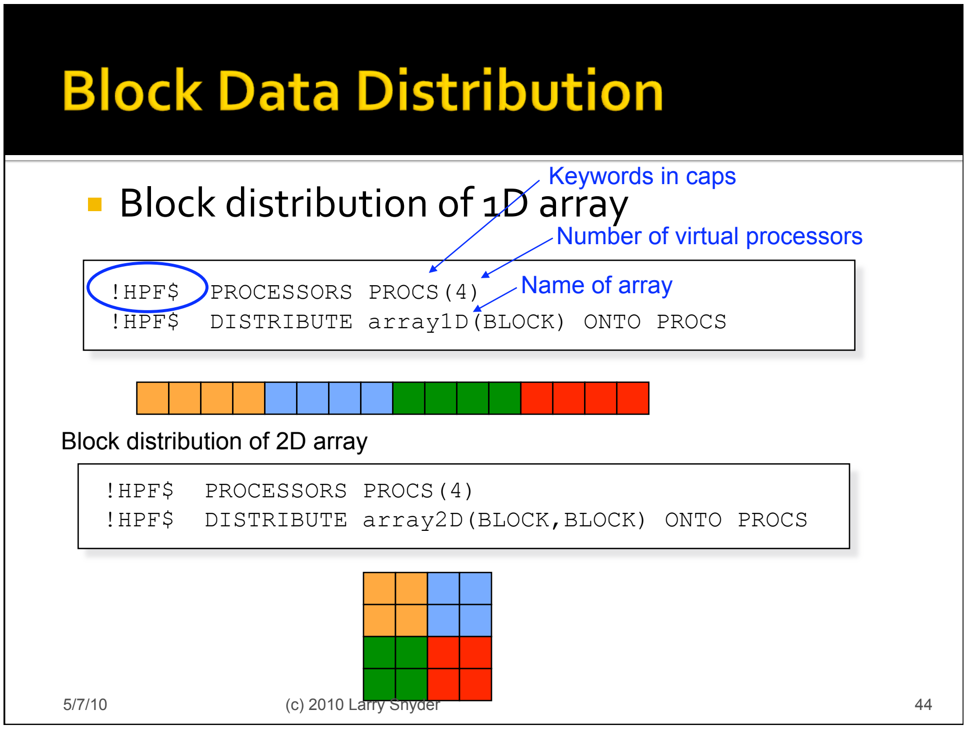
	0	0	0	0	
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
	1	1	1	1	



Jacobi Iteration in Fortran 90

- Example
  - The following statement computes the averaging step in the Jacobi iteration

```
next(2:n, 2:n) = (curr(1:n-1, 2:n) +
                  curr(3:n+1, 2:n) +
                  curr(2:n,   1:n-1)+
                  curr(2:n,   3:n+1)) / 4
```



Block Data Distribution

- Block distribution of 1D array

Keywords in caps

Number of virtual processors

Name of array

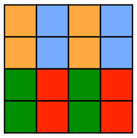
```
!HPF$  PROCESSORS  PROCS(4)
!HPF$  DISTRIBUTE  array1D(BLOCK)  ONTO  PROCS
```

Block distribution of 2D array

```
!HPF$  PROCESSORS  PROCS(4)
!HPF$  DISTRIBUTE  array2D(BLOCK,BLOCK)  ONTO  PROCS
```

Block-Cyclic Data Distribution

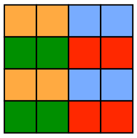
- Block-cyclic distribution



```
!HPF$  PROCESSORS PROCS(4)
!HPF$  DISTRIBUTE array2D(BLOCK, CYCLIC) ONTO PROCS
```

Block-cyclic distribution

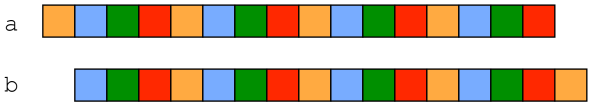
```
!HPF$  DISTRIBUTE array2D(CYCLIC, BLOCK) ONTO PROCS
```



Alignment Directives

- Arrays can be aligned with one another
  - Aligned elements will reside on the same physical processor
  - Alignment can reduce communication
  - Can align arrays of different dimensions

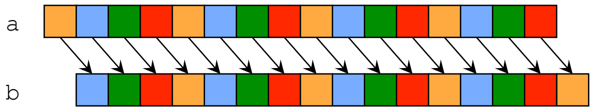
```
!HPF$  ALIGN a (i) WITH b(i-1)
```



Comm Implied by Distribution

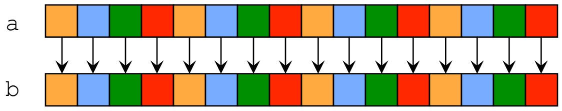
This alignment and assignment require all elements to be communicated to a different processor

```
!HPF$  ALIGN a(i) WITH b(i-1)
a(1:n) = b(1:n)
```

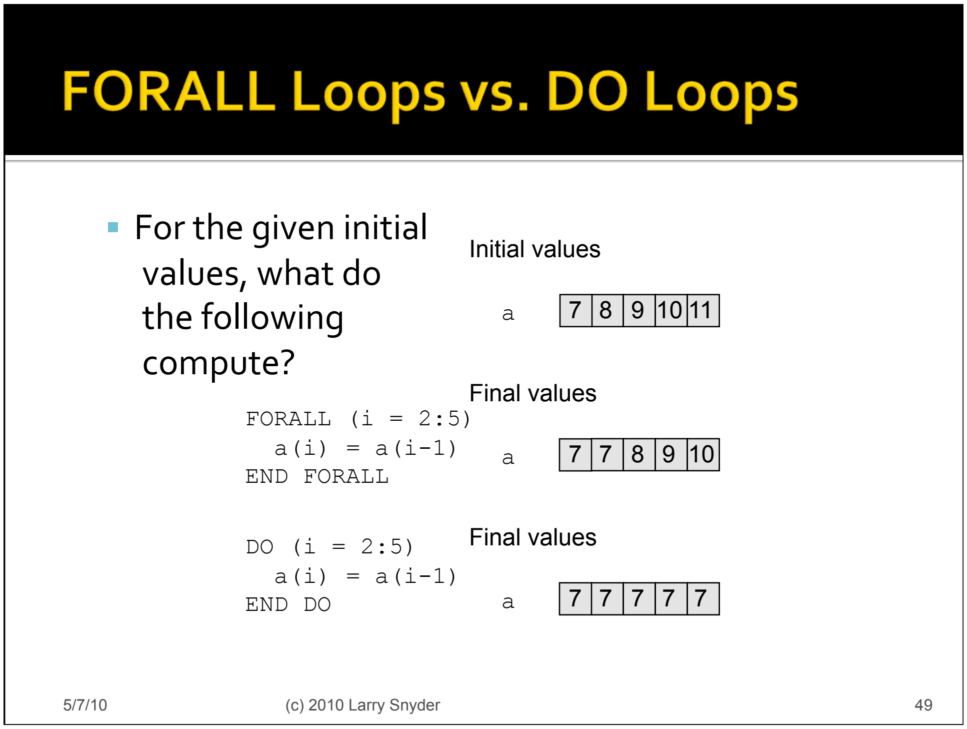


The following induces no communication

```
!HPF$  ALIGN a(i) WITH b(i)
```



Break



FORALL Loops vs. DO Loops

- For the given initial values, what do the following compute?

Initial values

a `7 8 9 10 11`

```
FORALL (i = 2:5)
  a(i) = a(i-1)
END FORALL
```

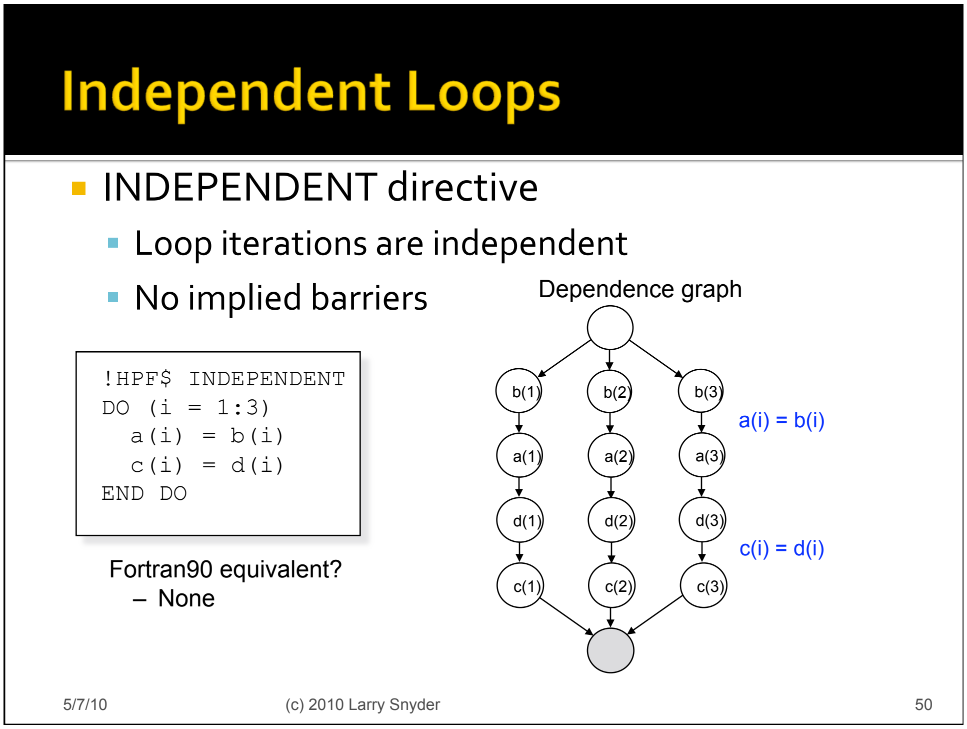
Final values

a `7 7 8 9 10`

```
DO (i = 2:5)
  a(i) = a(i-1)
END DO
```

Final values

a `7 7 7 7 7`



Independent Loops

- INDEPENDENT directive
  - Loop iterations are independent
  - No implied barriers

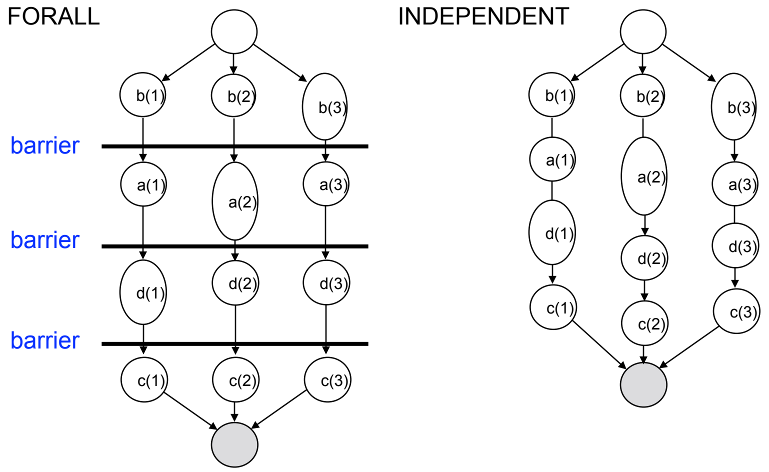
```
!HPF$ INDEPENDENT
DO (i = 1:3)
  a(i) = b(i)
  c(i) = d(i)
END DO
```

Fortran90 equivalent?
- None

Dependence graph

FORALL Loops vs. Independent Loops

- Is there a difference?

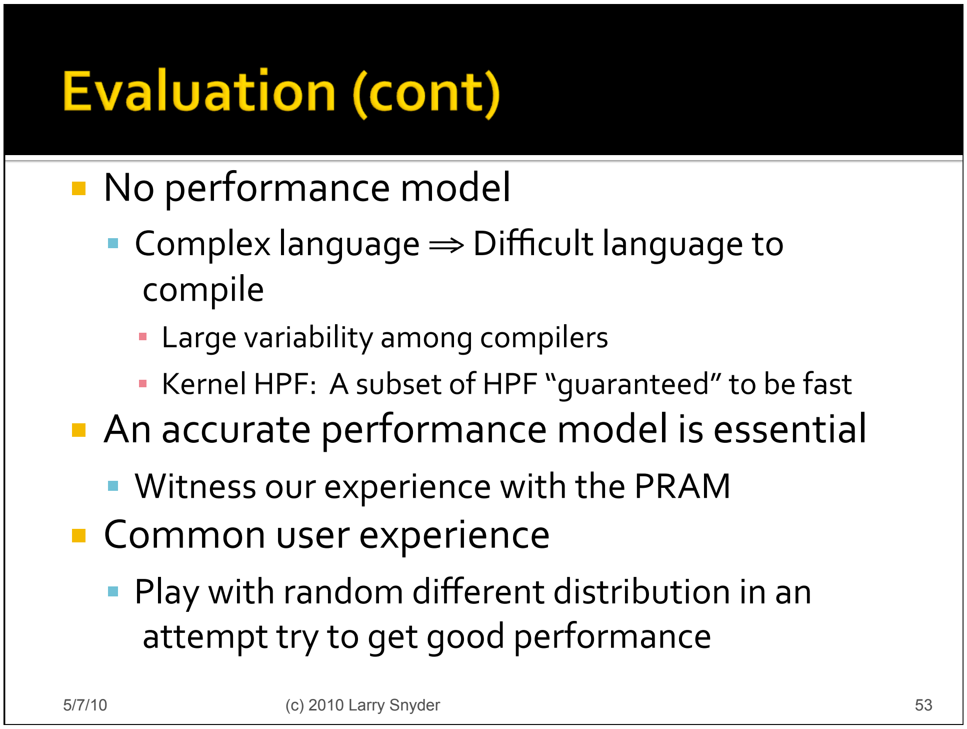


Evaluation

- Your thoughts on HPF?
  - Is this a convenient language to use?
  - Can programmers get good performance?
- No performance model
  - To understand locality and communication, need to understand complex interactions among distributions
    - Procedure calls are particularly bad
  - Many hidden costs
  - Small changes in distribution can have large performance impact

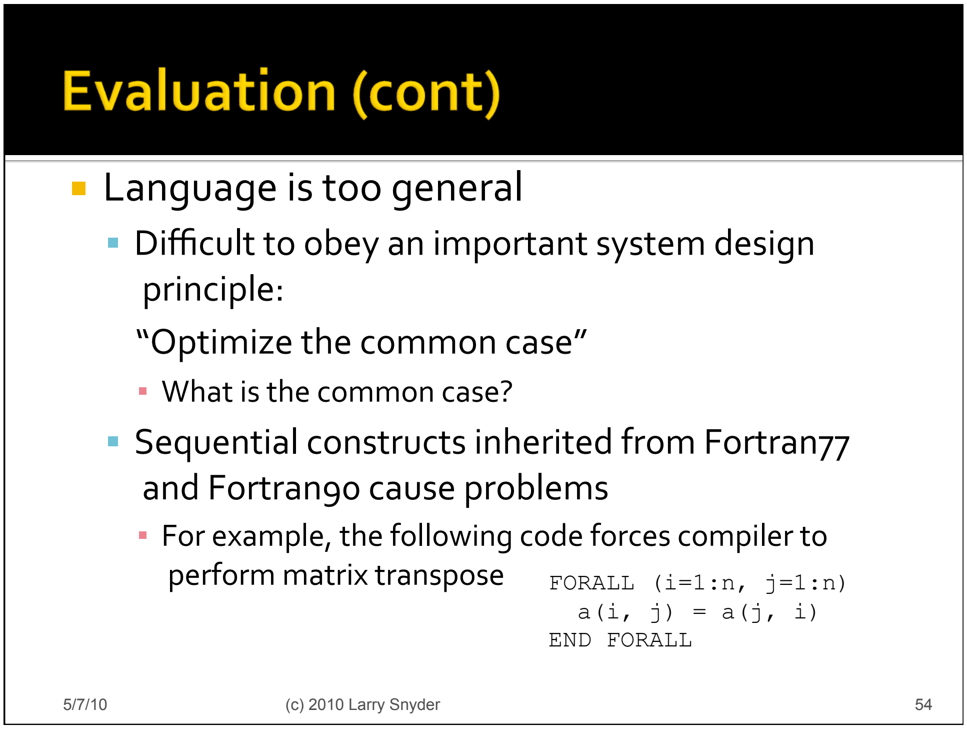
Does the following code induce communication?

```
a(i) = b(i)
```



Evaluation (cont)

- No performance model
  - Complex language ⇒ Difficult language to compile
    - Large variability among compilers
    - Kernel HPF: A subset of HPF “guaranteed” to be fast
- An accurate performance model is essential
  - Witness our experience with the PRAM
- Common user experience
  - Play with random different distribution in an attempt try to get good performance

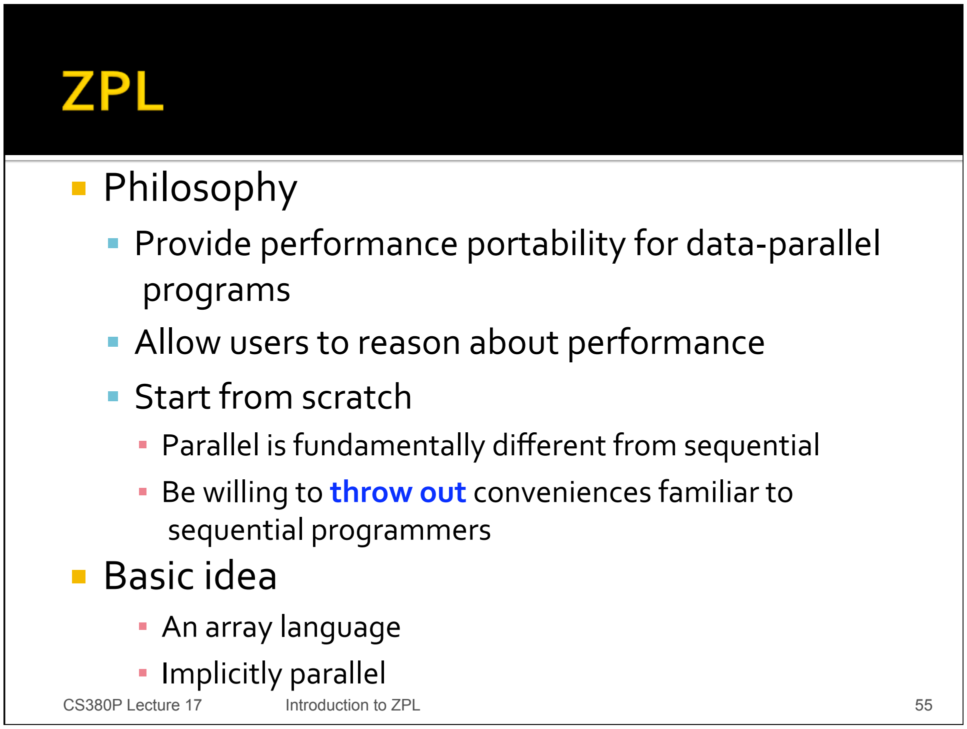


Evaluation (cont)

- Language is too general
  - Difficult to obey an important system design principle:

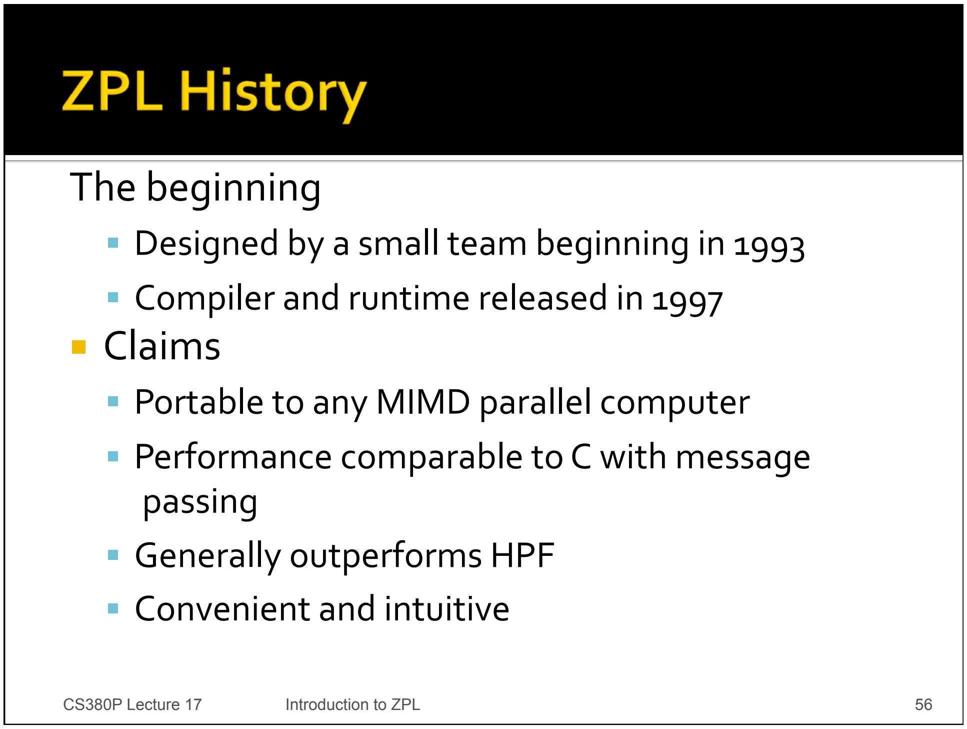
    “Optimize the common case”
    - What is the common case?
  - Sequential constructs inherited from Fortran77 and Fortran90 cause problems
    - For example, the following code forces compiler to perform matrix transpose

```
FORALL (i=1:n, j=1:n)
  a(i, j) = a(j, i)
END FORALL
```



ZPL

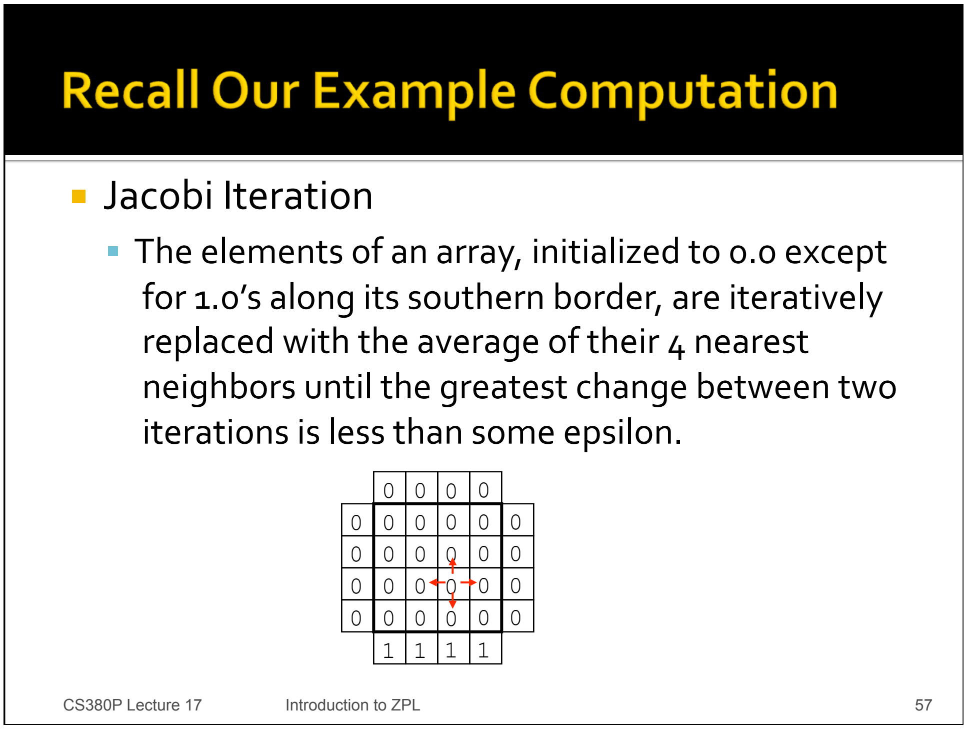
- Philosophy
  - Provide performance portability for data-parallel programs
  - Allow users to reason about performance
  - Start from scratch
    - Parallel is fundamentally different from sequential
    - Be willing to **throw out** conveniences familiar to sequential programmers
- Basic idea
    - An array language
    - Implicitly parallel



ZPL History

The beginning

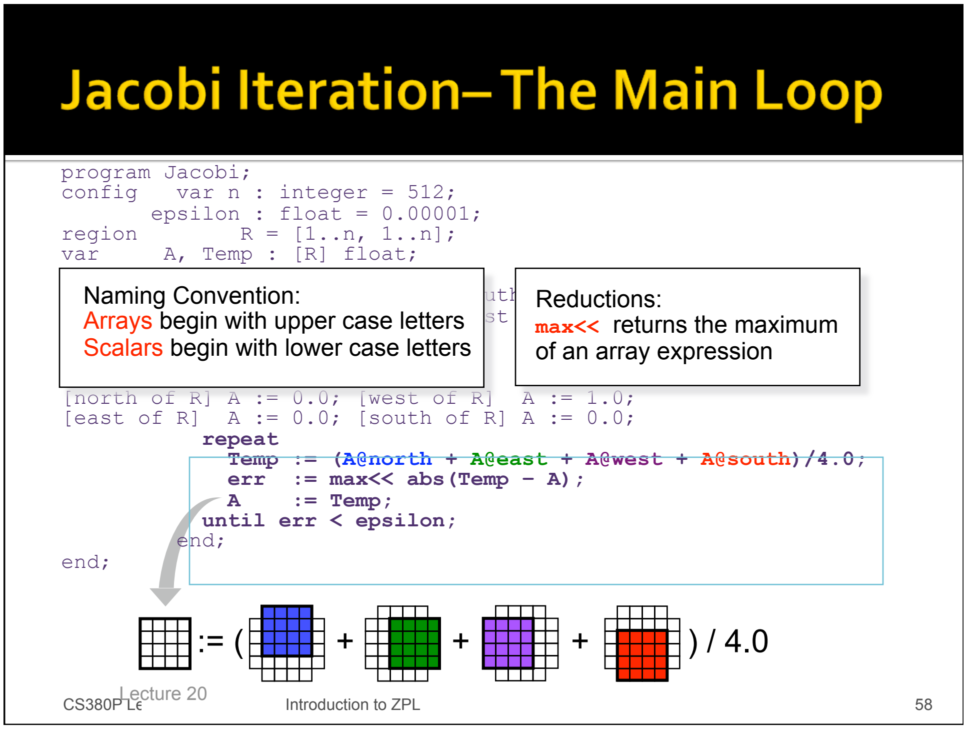
  - Designed by a small team beginning in 1993
  - Compiler and runtime released in 1997
- Claims
  - Portable to any MIMD parallel computer
  - Performance comparable to C with message passing
  - Generally outperforms HPF
  - Convenient and intuitive



Recall Our Example Computation

- Jacobi Iteration
  - The elements of an array, initialized to 0.0 except for 1.0's along its southern border, are iteratively replaced with the average of their 4 nearest neighbors until the greatest change between two iterations is less than some epsilon.

	0	0	0	0	
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
	1	1	1	1	



Jacobi Iteration– The Main Loop

```
program Jacobi;
config   var n : integer = 512;
       epsilon : float = 0.00001;
region        R = [1..n, 1..n];
var      A, Temp : [R] float;
                                 uth
                                 st
[north of R] A := 0.0; [west of R]  A := 1.0;
[east of R]  A := 0.0; [south of R] A := 0.0;
           repeat
             Temp := (A@north + A@east + A@west + A@south)/4.0;
             err  := max<< abs(Temp - A);
             A    := Temp;
           until err < epsilon;
         end;
end;
```

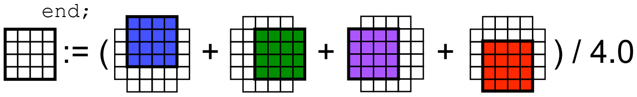
Naming Convention:
Arrays begin with upper case letters
Scalars begin with lower case letters

Reductions:
max<< returns the maximum of an array expression

Jacobi Iteration– The Region

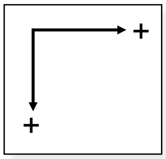
```
program Jacobi;
config    var n : integer = 512;
       epsilon : float = 0.00001;
region         R = [1..n, 1..n];
var        A, Temp : [R] float;
             err : float;
direction north = [-1, 0];      south = [ 1,  0];
          east  = [ 0, 1];      west  = [ 0, -1];
procedure Jacobi();
       [R] begin
             A := 0.0;
[north of R] A := 0.0; [west of R]  A := 1.0;
[east of R]  A := 0.0; [south of R] A := 0.0;
           repeat
             Temp  := (A@north + A@east + A@west + A@south)/4.0;
             err   := max<< abs(Temp - A);
             A     := Temp;
           until err < epsilon;
         end;
end;
```

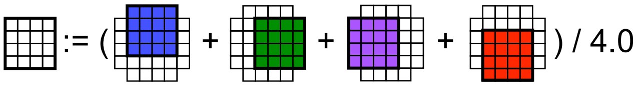
end;

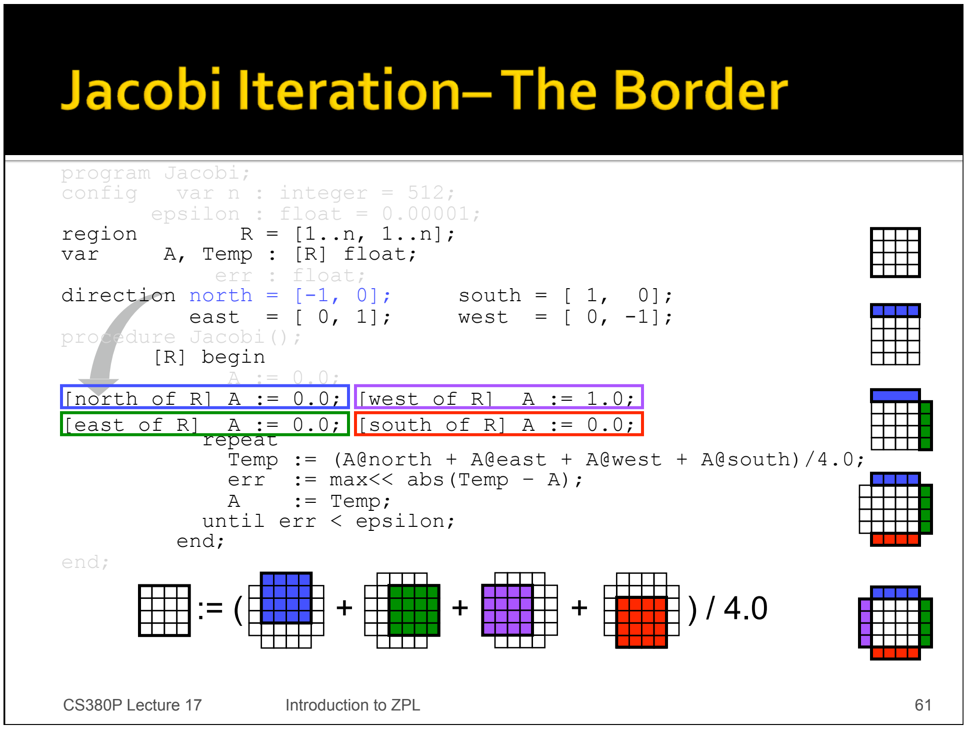


Jacobi Iteration– The Direction

```
program Jacobi;
config    var n : integer = 512;
       epsilon : float = 0.00001;
region         R = [1..n, 1..n];
var        A, Temp : [R] float;
             err : float;
direction north = [-1, 0];      south = [ 1,  0];
          east  = [ 0, 1];      west  = [ 0, -1];
procedure Jacobi();
       [R] begin
             A := 0.0;
[north of R] A := 0.0; [west of R]  A := 1.0;
[east of R]  A := 0.0; [south of R] A := 0.0;
           repeat
             Temp  := (A@north + A@east + A@west + A@south)/4.0;
             err   := max<< abs(Temp - A);
             A     := Temp;
           until err < epsilon;
         end;
end;
```

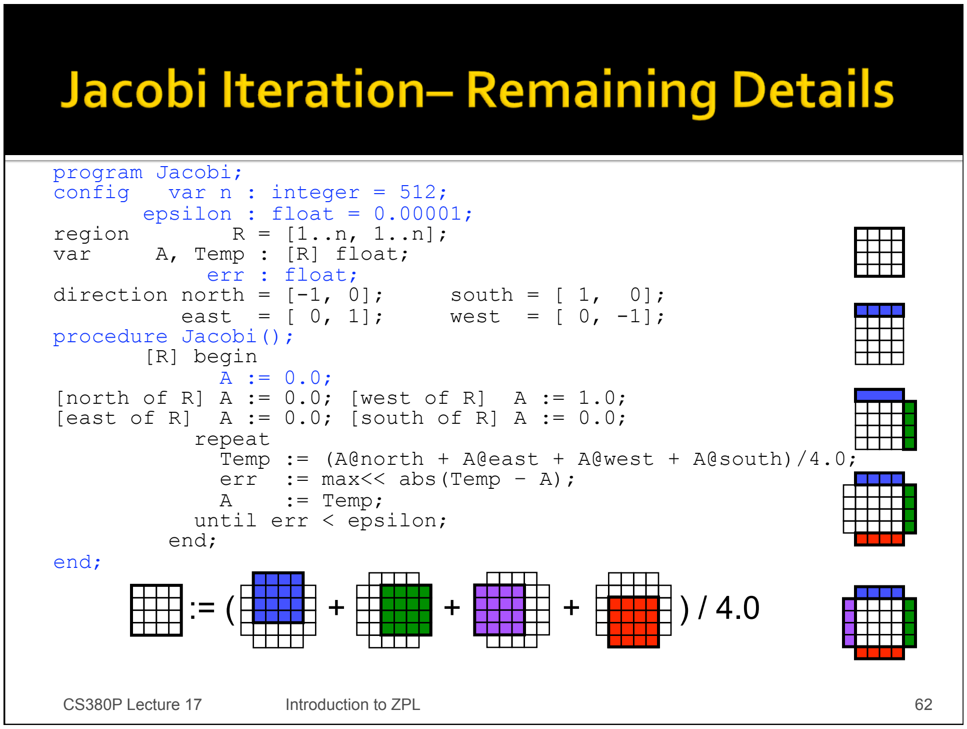






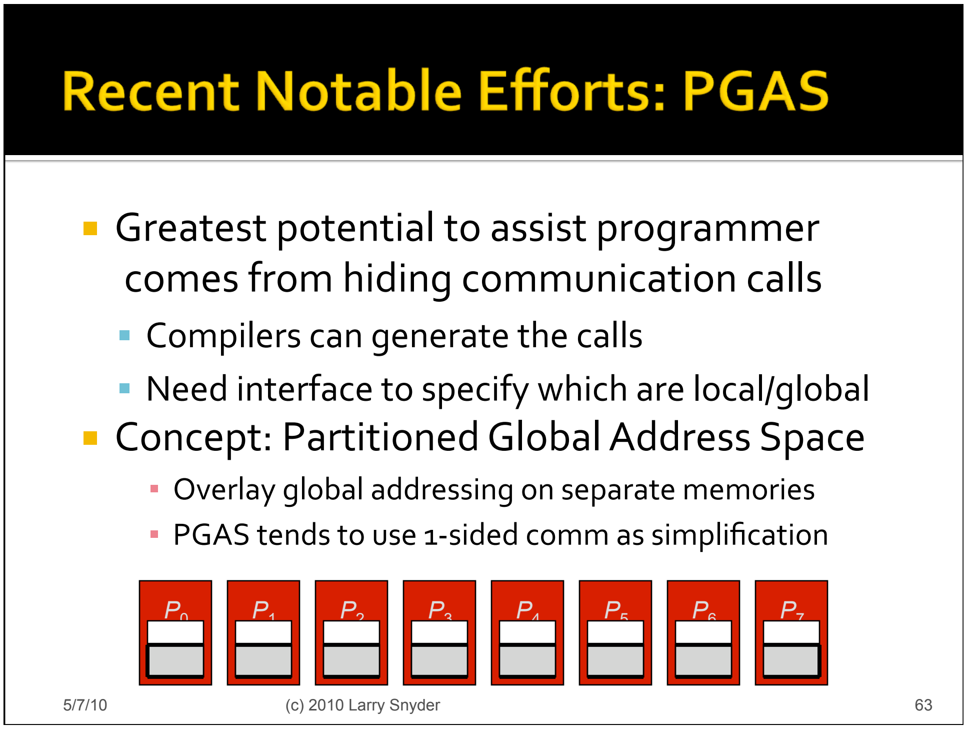
Jacobi Iteration– The Border

```
program Jacobi;
config   var n : integer = 512;
       epsilon : float = 0.00001;
region        R = [1..n, 1..n];
var     A, Temp : [R] float;
            err : float;
direction north = [-1, 0];      south = [ 1,  0];
          east  = [ 0, 1];      west  = [ 0, -1];
procedure Jacobi();
       [R] begin
             A := 0.0;
[north of R] A := 0.0; [west of R]  A := 1.0;
[east of R]  A := 0.0; [south of R] A := 0.0;
           repeat
             Temp := (A@north + A@east + A@west + A@south)/4.0;
             err  := max<< abs(Temp - A);
             A    := Temp;
           until err < epsilon;
         end;
end;
```



Jacobi Iteration– Remaining Details

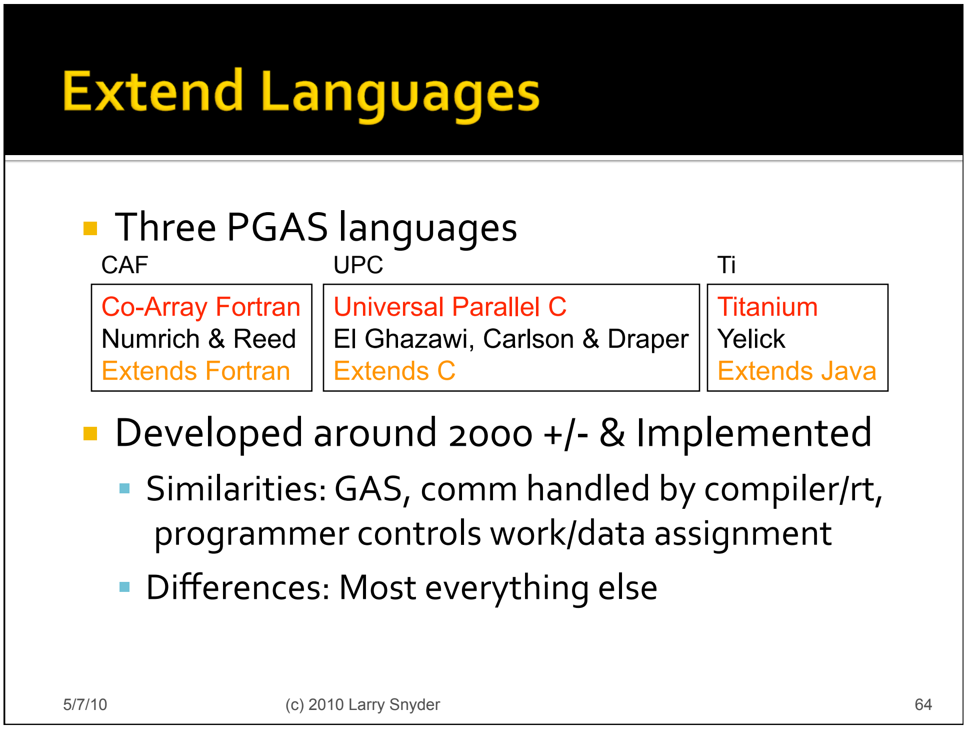
```
program Jacobi;
config   var n : integer = 512;
       epsilon : float = 0.00001;
region        R = [1..n, 1..n];
var     A, Temp : [R] float;
            err : float;
direction north = [-1, 0];      south = [ 1,  0];
          east  = [ 0, 1];      west  = [ 0, -1];
procedure Jacobi();
       [R] begin
             A := 0.0;
[north of R] A := 0.0; [west of R]  A := 1.0;
[east of R]  A := 0.0; [south of R] A := 0.0;
           repeat
             Temp := (A@north + A@east + A@west + A@south)/4.0;
             err  := max<< abs(Temp - A);
             A    := Temp;
           until err < epsilon;
         end;
end;
```



Recent Notable Efforts: PGAS

- Greatest potential to assist programmer comes from hiding communication calls
  - Compilers can generate the calls
  - Need interface to specify which are local/global
- Concept: Partitioned Global Address Space
  - Overlay global addressing on separate memories
  - PGAS tends to use 1-sided comm as simplification

P_0
P_1
P_2
P_3
P_4
P_5
P_6
P_7

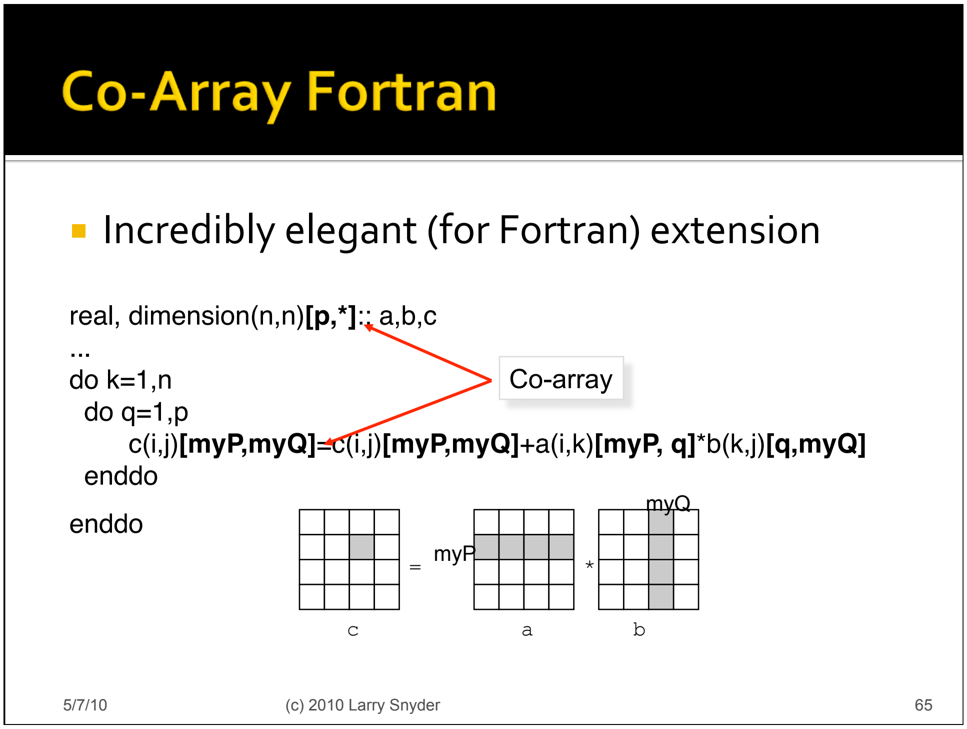


Extend Languages

- Three PGAS languages

CAF	UPC	Ti
Co-Array Fortran Numrich & Reed Extends Fortran	Universal Parallel C El Ghazawi, Carlson & Draper Extends C	Titanium Yelick Extends Java

- Developed around 2000 +/- & Implemented
  - Similarities: GAS, comm handled by compiler/rt, programmer controls work/data assignment
  - Differences: Most everything else

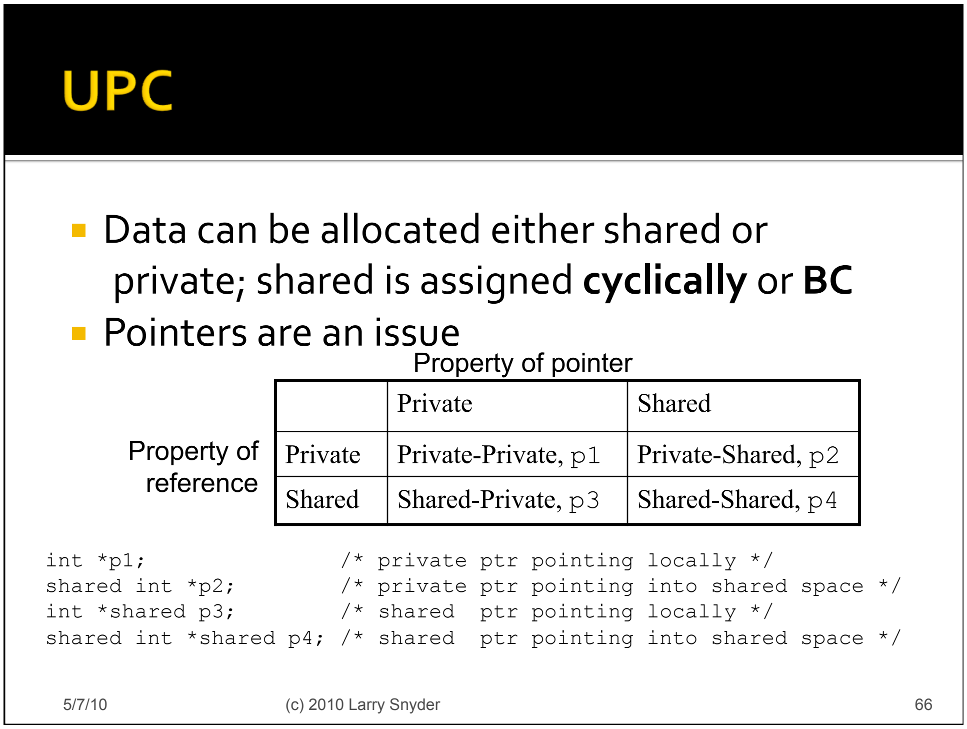


Co-Array Fortran

- Incredibly elegant (for Fortran) extension

```
real, dimension(n,n)[p,*]:: a,b,c
...
do k=1,n
  do q=1,p
      c(i,j)[myP,myQ]=c(i,j)[myP,myQ]+a(i,k)[myP, q]*b(k,j)[q,myQ]
  enddo
enddo
```

Co-array



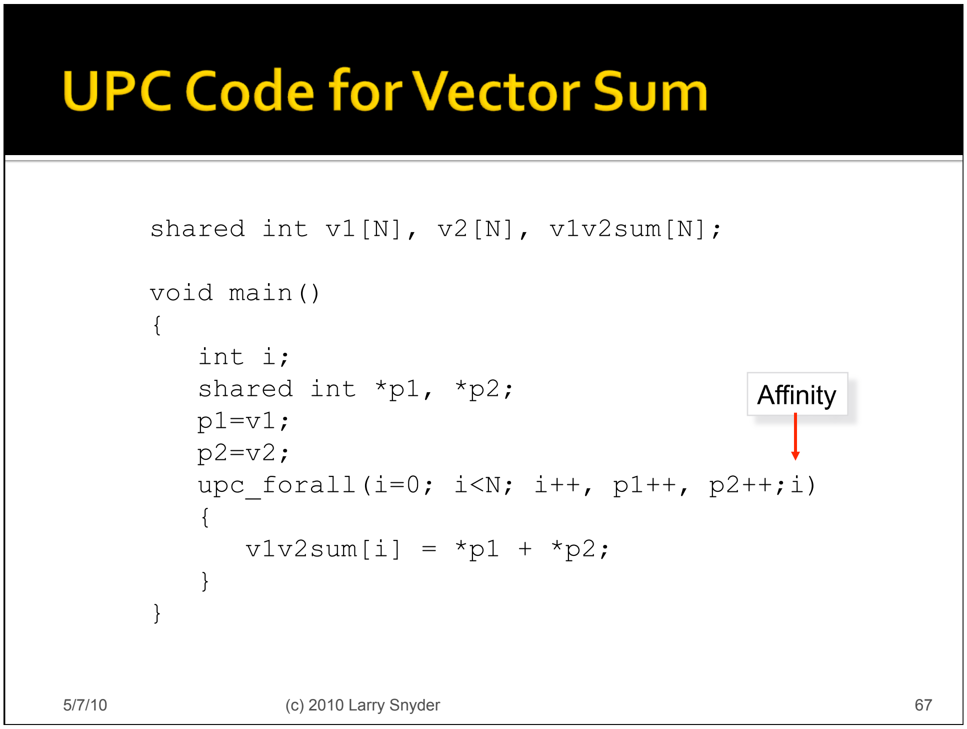
UPC

- Data can be allocated either shared or private; shared is assigned **cyclically** or **BC**
- Pointers are an issue

Property of pointer

Property of reference		Private	Shared
	Private	Private-Private, p1	Private-Shared, p2
	Shared	Shared-Private, p3	Shared-Shared, p4

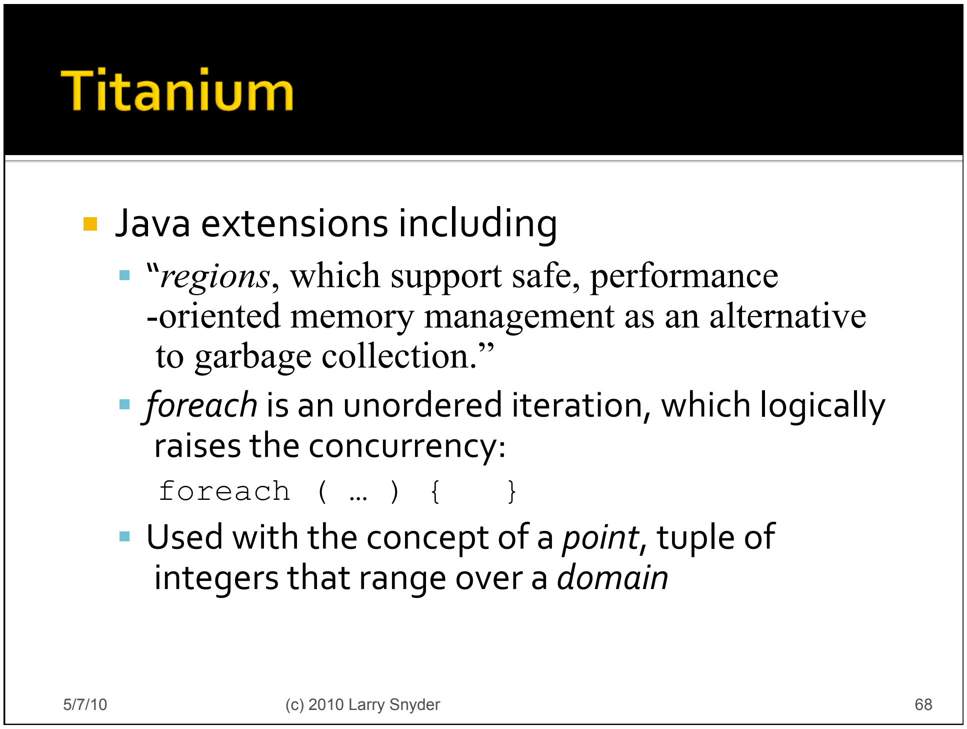
```
int *p1;                /* private ptr pointing locally */
shared int *p2;         /* private ptr pointing into shared space */
int *shared p3;         /* shared  ptr pointing locally */
shared int *shared p4;  /* shared  ptr pointing into shared space */
```



UPC Code for Vector Sum

```
shared int v1[N], v2[N], v1v2sum[N];

void main()
{
   int i;
   shared int *p1, *p2;
   p1=v1;
   p2=v2;
   upc_forall(i=0; i<N; i++, p1++, p2++;i)
   {
      v1v2sum[i] = *p1 + *p2;
   }
}
```

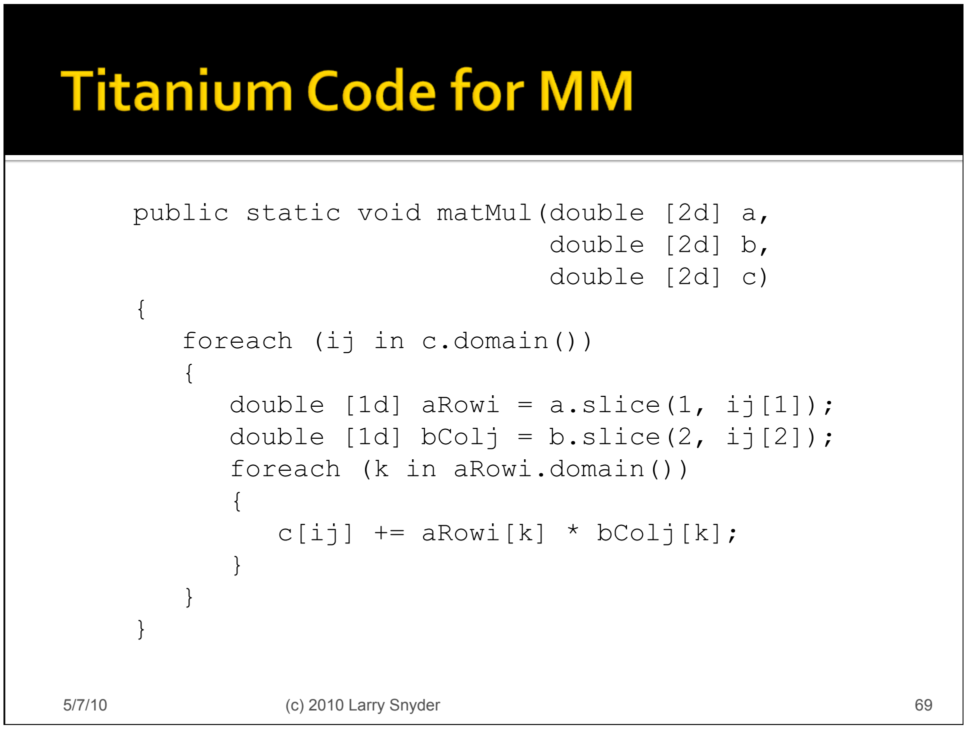
Affinity



Titanium

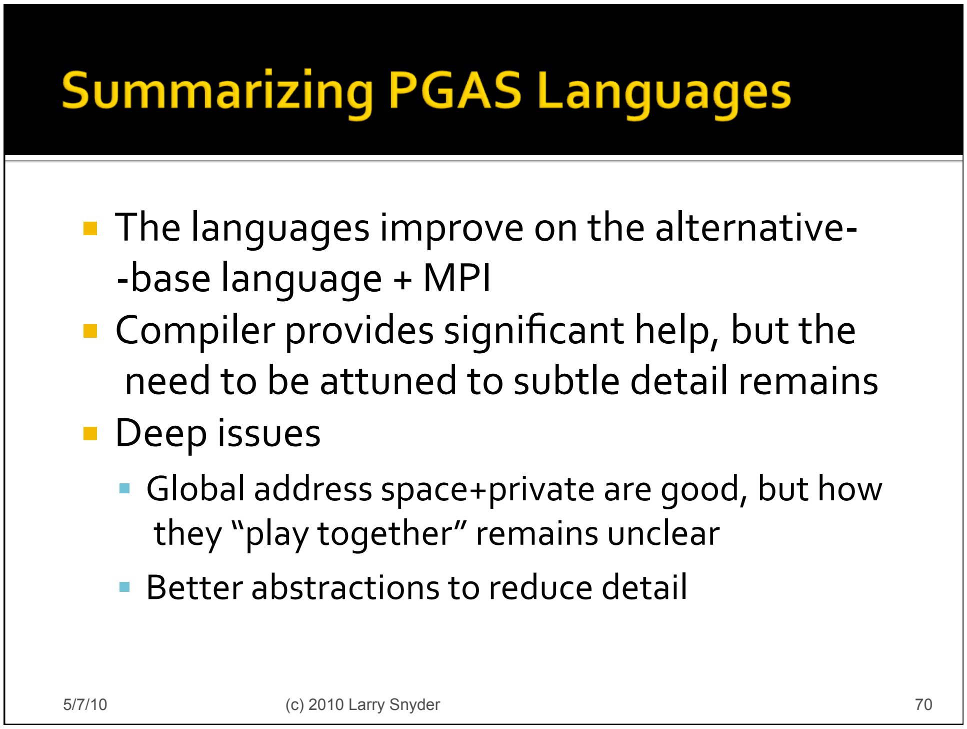
- Java extensions including
  - "*regions*, which support safe, performance -oriented memory management as an alternative to garbage collection."
  - *foreach* is an unordered iteration, which logically raises the concurrency:

    `foreach ( … ) {    }`
  - Used with the concept of a *point*, tuple of integers that range over a *domain*



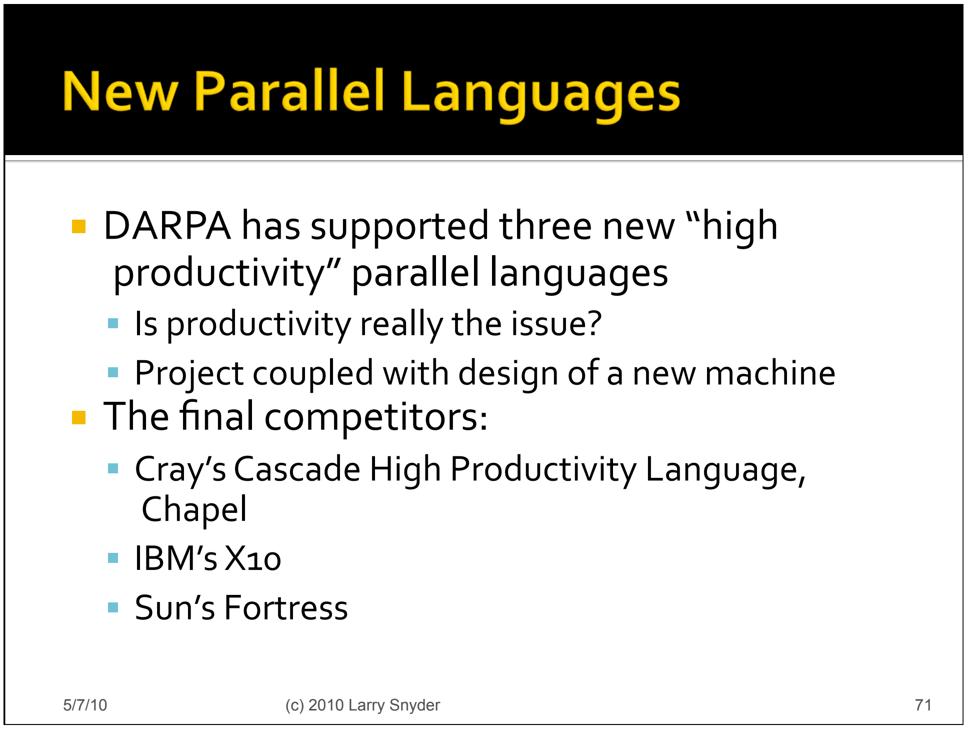
Titanium Code for MM

```
public static void matMul(double [2d] a,
                          double [2d] b,
                          double [2d] c)
{
   foreach (ij in c.domain())
   {
      double [1d] aRowi = a.slice(1, ij[1]);
      double [1d] bColj = b.slice(2, ij[2]);
      foreach (k in aRowi.domain())
      {
         c[ij] += aRowi[k] * bColj[k];
      }
   }
}
```



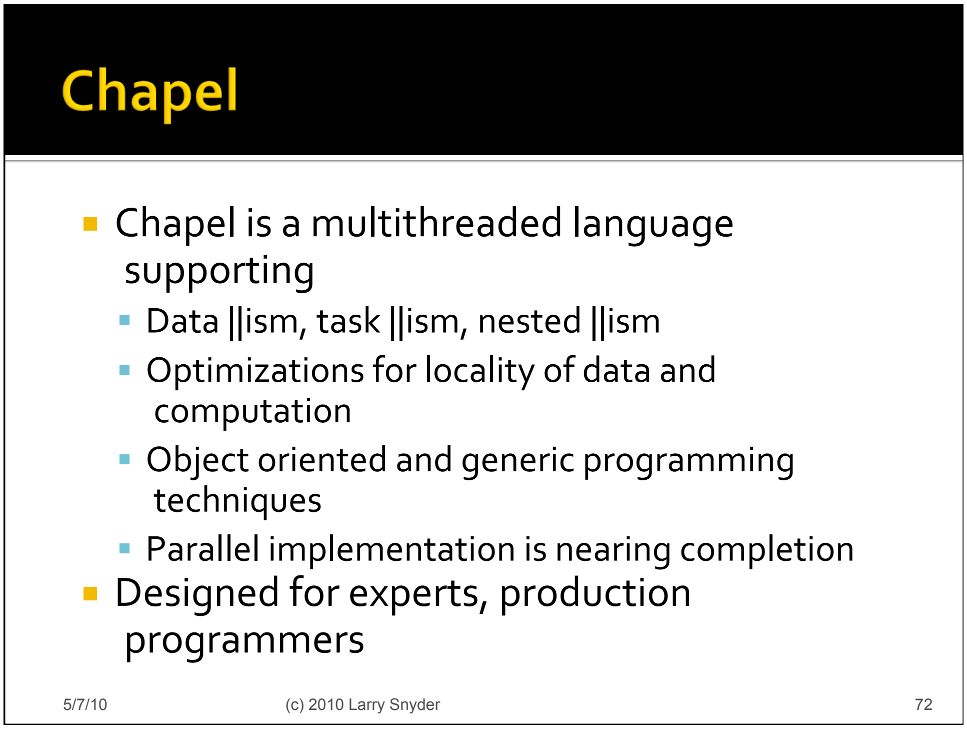
Summarizing PGAS Languages

- The languages improve on the alternative- -base language + MPI
- Compiler provides significant help, but the need to be attuned to subtle detail remains
- Deep issues
  - Global address space+private are good, but how they "play together" remains unclear
  - Better abstractions to reduce detail



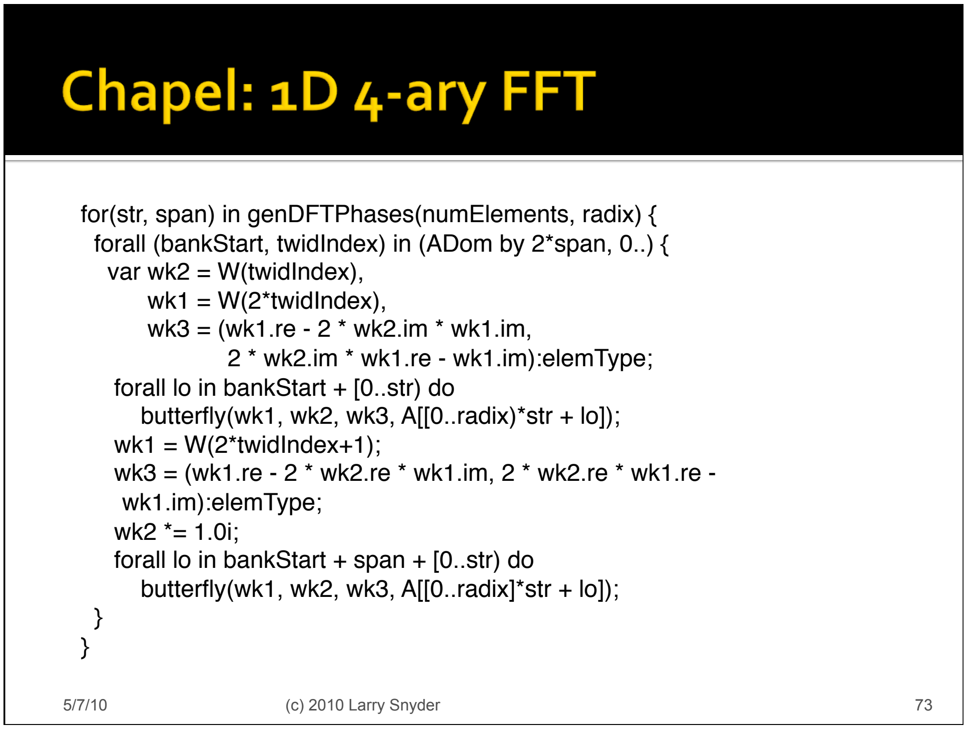
New Parallel Languages

- DARPA has supported three new “high productivity” parallel languages
  - Is productivity really the issue?
  - Project coupled with design of a new machine
- The final competitors:
  - Cray’s Cascade High Productivity Language, Chapel
  - IBM’s X10
  - Sun’s Fortress



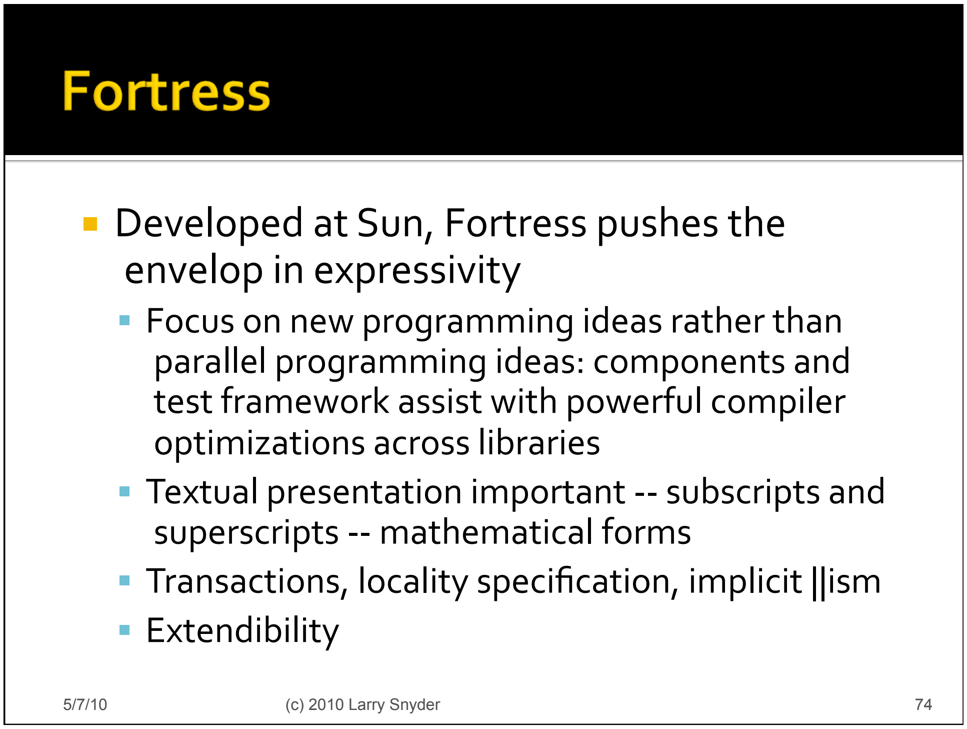
Chapel

- Chapel is a multithreaded language supporting
  - Data ||ism, task ||ism, nested ||ism
  - Optimizations for locality of data and computation
  - Object oriented and generic programming techniques
  - Parallel implementation is nearing completion
- Designed for experts, production programmers



Chapel: 1D 4-ary FFT

```
for(str, span) in genDFTPhases(numElements, radix) {
  forall (bankStart, twidIndex) in (ADom by 2*span, 0..) {
    var wk2 = W(twidIndex),
          wk1 = W(2*twidIndex),
          wk3 = (wk1.re - 2 * wk2.im * wk1.im,
                      2 * wk2.im * wk1.re - wk1.im):elemType;
     forall lo in bankStart + [0..str) do
         butterfly(wk1, wk2, wk3, A[[0..radix)*str + lo]);
     wk1 = W(2*twidIndex+1);
     wk3 = (wk1.re - 2 * wk2.re * wk1.im, 2 * wk2.re * wk1.re -
      wk1.im):elemType;
     wk2 *= 1.0i;
     forall lo in bankStart + span + [0..str) do
         butterfly(wk1, wk2, wk3, A[[0..radix]*str + lo]);
  }
}
```

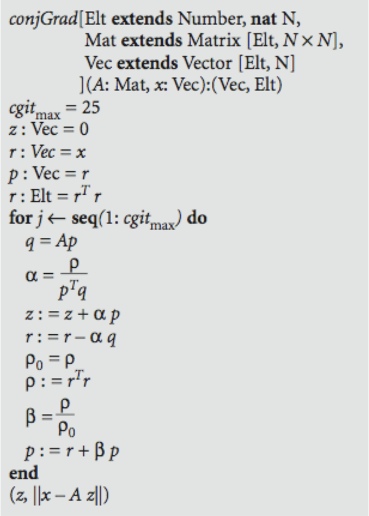


Fortress

- Developed at Sun, Fortress pushes the envelop in expressivity
  - Focus on new programming ideas rather than parallel programming ideas: components and test framework assist with powerful compiler optimizations across libraries
  - Textual presentation important -- subscripts and superscripts -- mathematical forms
  - Transactions, locality specification, implicit ||ism
  - Extendibility

Fortress

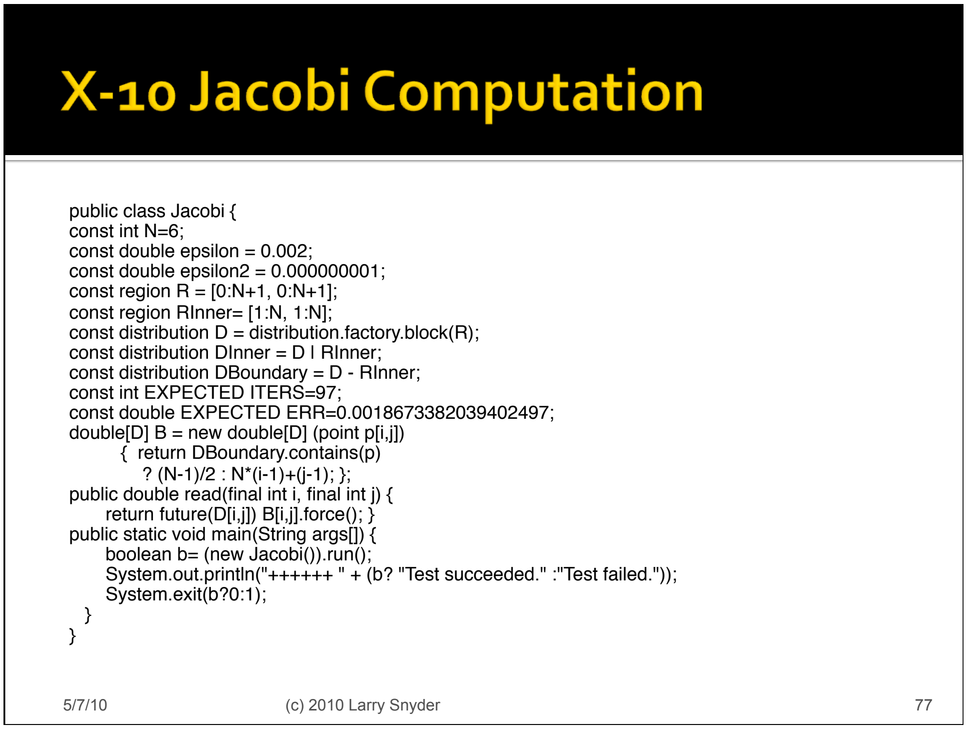
- Conjugate gradient program in Fortress
- Features
  - := / =
  - Sequential
  - Mathematical



```
conjGrad[Elt extends Number, nat N,
         Mat extends Matrix [Elt, $N \times N$],
         Vec extends Vector [Elt, N]
        ](A: Mat, x: Vec):(Vec, Elt)
$cgit_{\max} = 25$
$z$ : Vec = 0
$r$ : Vec = $x$
$p$ : Vec = $r$
$r$ : Elt = $r^T r$
for $j \leftarrow$ seq(1: $cgit_{\max}$) do
   $q = Ap$
   $\alpha = \frac{\rho}{p^T q}$
   $z := z + \alpha p$
   $r := r - \alpha q$
   $\rho_0 = \rho$
   $\rho := r^T r$
   $\beta = \frac{\rho}{\rho_0}$
   $p := r + \beta p$
end
$(z, \|x - A z\|)$
```

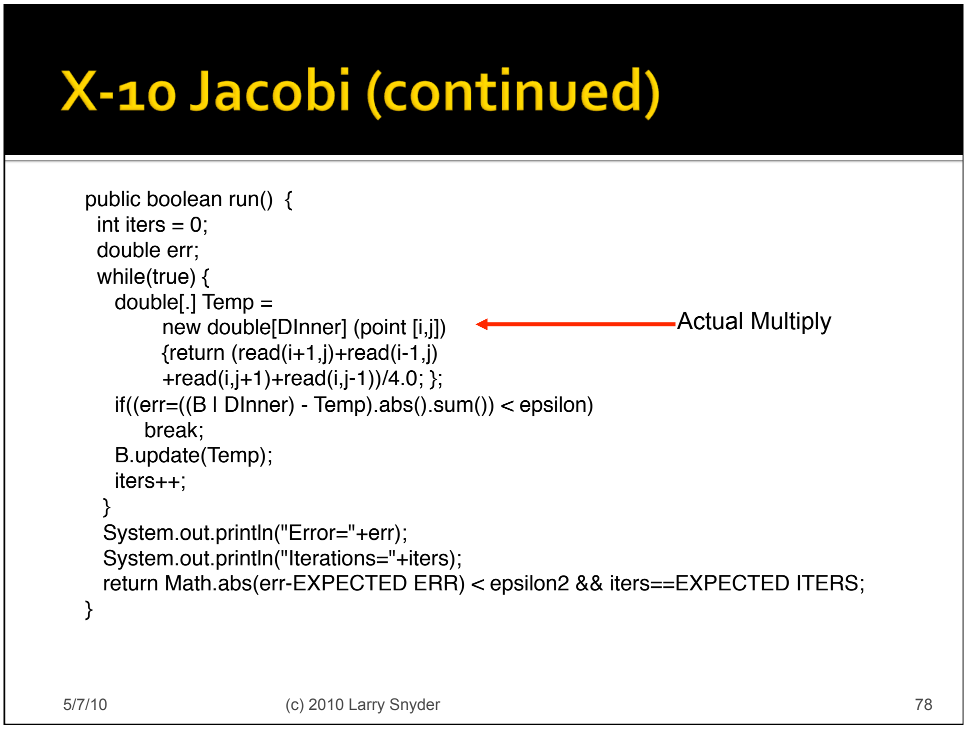
X-10

- IBM's X10 is a type safe, distributed object oriented language in the PGAS family -- its "accessible to Java programmers"
- Many goodies including regions (a la ZPL), places (for locality), asynch, futures, foreach, ateach, atomic blocks and global manipulation of data structures



X-10 Jacobi Computation

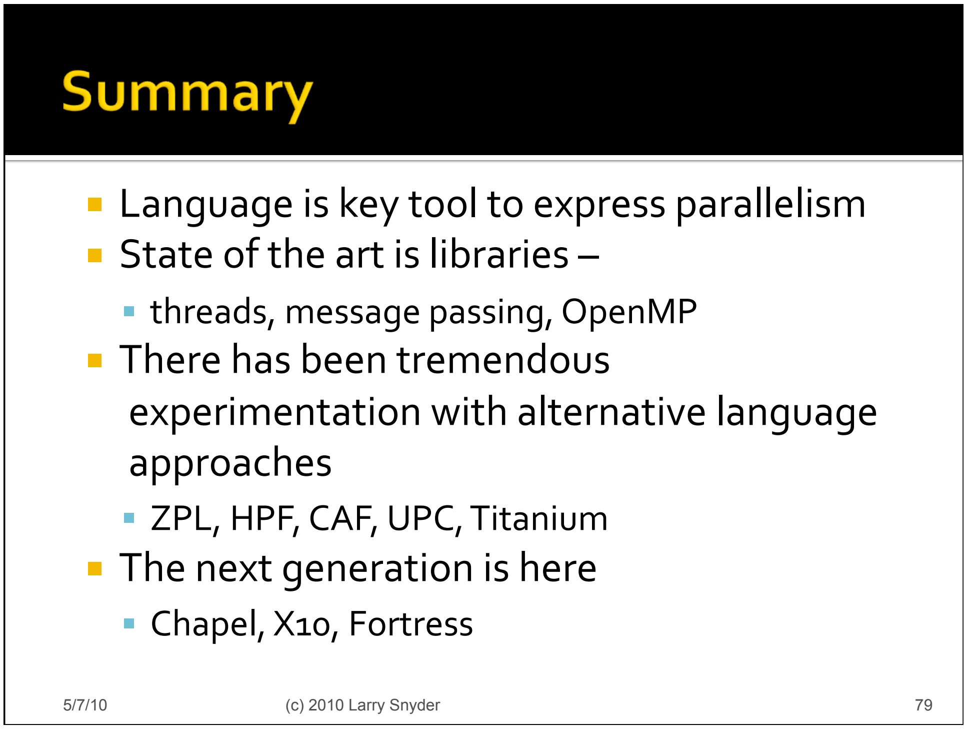
```
public class Jacobi {
const int N=6;
const double epsilon = 0.002;
const double epsilon2 = 0.000000001;
const region R = [0:N+1, 0:N+1];
const region RInner= [1:N, 1:N];
const distribution D = distribution.factory.block(R);
const distribution DInner = D | RInner;
const distribution DBoundary = D - RInner;
const int EXPECTED ITERS=97;
const double EXPECTED ERR=0.0018673382039402497;
double[D] B = new double[D] (point p[i,j])
        {  return DBoundary.contains(p)
            ? (N-1)/2 : N*(i-1)+(j-1); };
public double read(final int i, final int j) {
      return future(D[i,j]) B[i,j].force(); }
public static void main(String args[]) {
      boolean b= (new Jacobi()).run();
      System.out.println("++++++ " + (b? "Test succeeded." :"Test failed."));
      System.exit(b?0:1);
   }
}
```



X-10 Jacobi (continued)

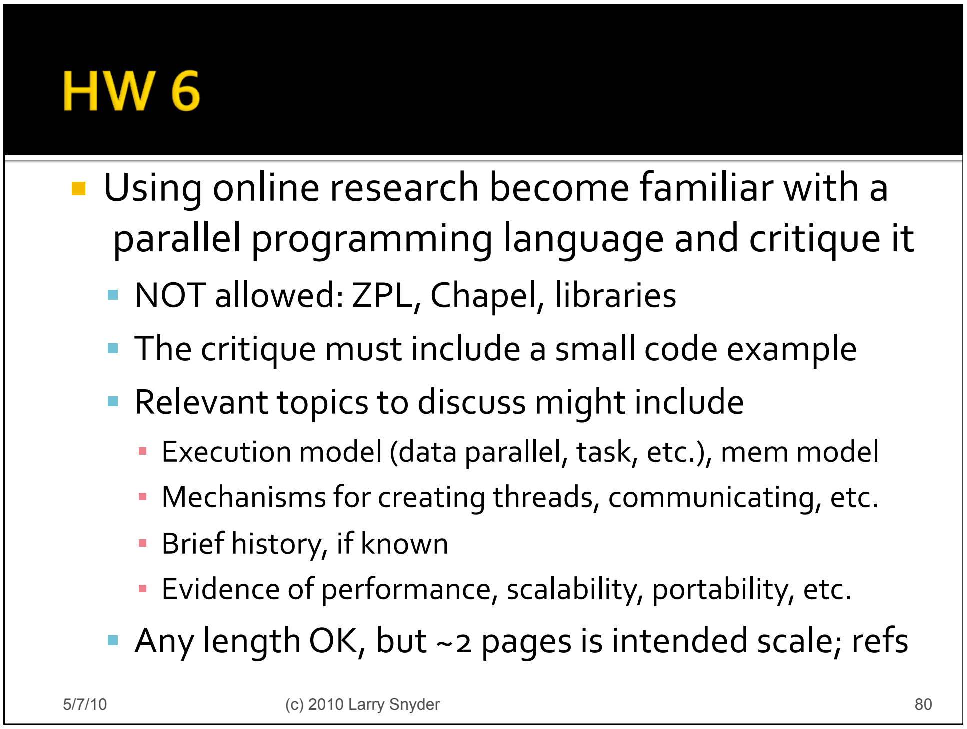
```
public boolean run()  {
  int iters = 0;
  double err;
  while(true) {
     double[.] Temp =
            new double[DInner] (point [i,j])
            {return (read(i+1,j)+read(i-1,j)
            +read(i,j+1)+read(i,j-1))/4.0; };
     if((err=((B | DInner) - Temp).abs().sum()) < epsilon)
          break;
     B.update(Temp);
     iters++;
   }
   System.out.println("Error="+err);
   System.out.println("Iterations="+iters);
   return Math.abs(err-EXPECTED ERR) < epsilon2 && iters==EXPECTED ITERS;
}
```

Actual Multiply



Summary

- Language is key tool to express parallelism
- State of the art is libraries –
  - threads, message passing, OpenMP
- There has been tremendous experimentation with alternative language approaches
  - ZPL, HPF, CAF, UPC, Titanium
- The next generation is here
  - Chapel, X10, Fortress



HW 6

- Using online research become familiar with a parallel programming language and critique it
  - NOT allowed: ZPL, Chapel, libraries
  - The critique must include a small code example
  - Relevant topics to discuss might include
    - Execution model (data parallel, task, etc.), mem model
    - Mechanisms for creating threads, communicating, etc.
    - Brief history, if known
    - Evidence of performance, scalability, portability, etc.
  - Any length OK, but ~2 pages is intended scale; refs