Overview

A. Introduction to PGAS (~ 30 mts)

B. Introduction to Languages
   A. UPC (~ 65 mts)
   B. X10 (~ 65 mts)
   C. Chapel (~ 65 mts)

C. **Comparison of Languages (~45 minutes)**
   A. **Comparative Heat transfer Example**
   B. **Comparative Summary of features**
   C. **Discussion**

D. Hands-On (90 mts)

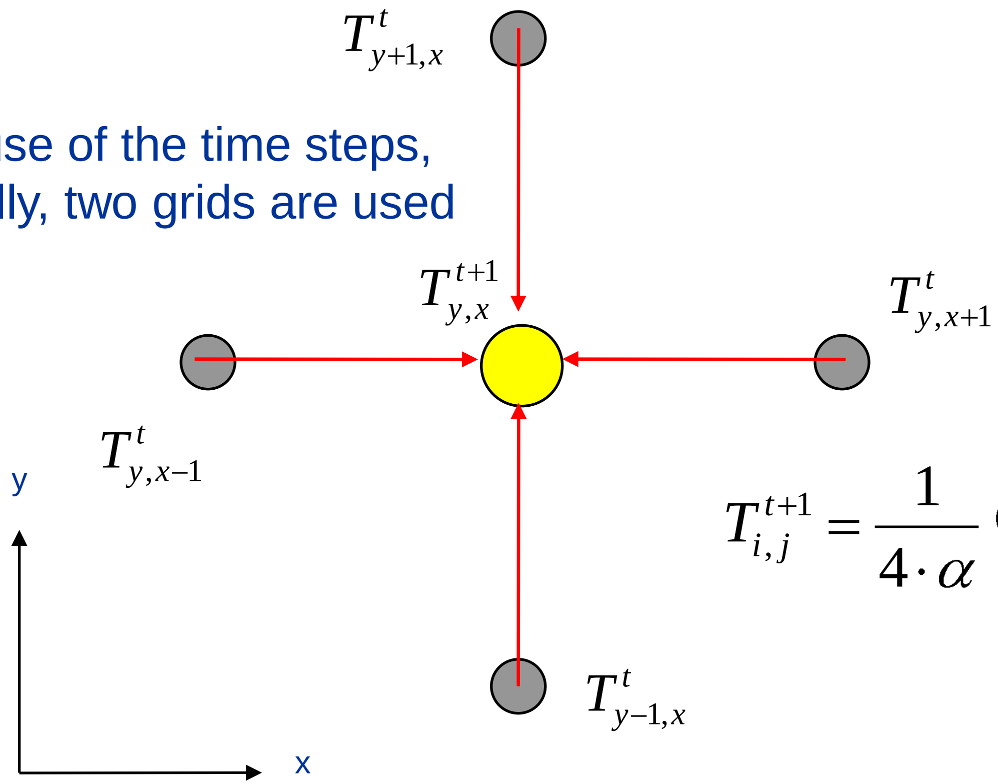
Comparison of Languages

UPC

2D Heat Conduction Problem

- Based on the 2D Partial Differential Equation (1), 2D Heat Conduction problem is similar to a 4-point stencil operation, as seen in (2):

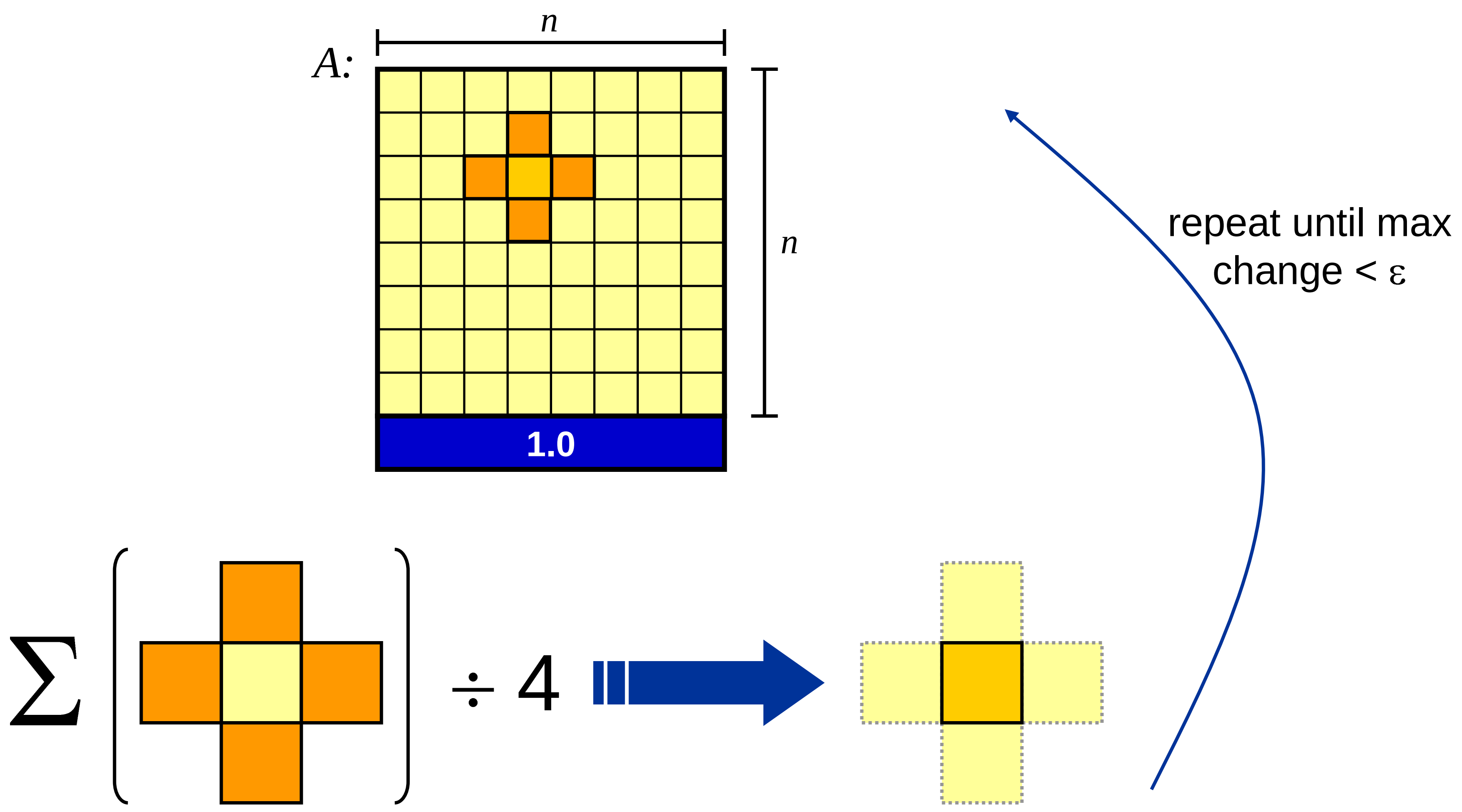
Because of the time steps, Typically, two grids are used



$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

$$T^{t+1}_{i,j} = \frac{1}{4\cdot\alpha}\left(T^{t}_{i-1,j} + T^{t}_{i+1,j} + T^{t}_{i,j-1} + T^{t}_{i,j+1}\right) \quad (2)$$

Heat Transfer in Pictures



2D Heat Conduction Problem

```
shared [BLOCKSIZE] double grids[2][N][N];
shared double dTmax_local[THREADS], dTmax_shared;
int x, y, nr_iter = 0, finished = 0;
int dg = 1, sg = 0;
double dTmax, dT, T, epsilon = 0.0001;
do {
   dTmax = 0.0;
   for( y=1; y<N-1; y++ ){
     upc_forall( x=1; x<N-1; x++; &grids[sg][y][x] ){
       T = (grids[sg][y-1][x] + grids[sg][y+1][x] +
         grids[sg][y][x-1] + grids[sg][y][x+1])
           / 4.0;
         dT = T – grids[sg][y][x];
         grids[dg][y][x] = T;
         if( dTmax < fabs(dT) )
           dTmax = fabs(dT);
     }
   }
```

Affinity field, used for work distribution

4-pt stencil

2D Heat Conduction Problem

```
dTmax_local[MYTHREAD]=dTmax;

upc_all_reduceD(
   &dTmax_shared,
   dTmax_local, UPC_MAX,
   THREADS, 1, NULL,
   UPC_IN_ALLSYNC |
   UPC_OUT_ALLSYNC );
```

reduction operation using UPC collectives library

```
 if( dTmax_shared < epsilon )
  finished = 1;
 else{
/*swapping the source &
   destination "pointers"*/
  dg = sg;
  sg = !sg;
 }
  nr_iter++;
} while( !finished );
upc_barrier;
```

Comparison of Languages

X10

Heat transfer in X10

- X10 permits smooth variation between multiple concurrency styles
  - "High-level" ZPL-style (operations on global arrays)
    - Chapel "global view" style
    - Expressible, but relies on "compiler magic" for performance
  - OpenMP style
    - Chunking within a single place
  - MPI-style
    - SPMD computation with explicit all-to-all reduction
    - Uses clocks
  - "OpenMP within MPI" style
    - For hierarchical parallelism
    - Fairly easy to derive from ZPL-style program.

Heat Transfer in X10 – ZPL style

```
class Stencil2D {
  static type Real=Double;
  const n = 6, epsilon = 1.0e-5;

  const BigD = Dist.makeBlock([0..n+1, 0..n+1]),
        D = BigD | [1..n, 1..n],
        LastRow = [0..0, 1..n] to Region;
  val A = Array.make[Real](BigD), Temp = Array.make[Real](BigD);
  {
    A(LastRow) = 1.0D;
  }
  def run() {
    do {
      finish ateach (p in D)
        Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;

      val delta = (A(D)-Temp(D)).lift(Math.abs).reduce(Math.max, 0.0);
      A(D) = Temp(D);
    } while (delta > epsilon);
  }
}
```

Heat Transfer in X10 – ZPL style

- Cast in fork-join style rather than SPMD style
  - Compiler needs to transform into SPMD style
- Compiler needs to chunk iterations per place
  - Fine grained iteration has too much overhead
- Compiler needs to generate code for distributed array operations
  - Create temporary global arrays, hoist them out of loop, etc.
- Uses implicit syntax to access remote locations.

Simple to write — tough to implement efficiently

Heat Transfer in X10 – II

```
def run() {
  val D_Base = Dist.makeUnique(D.places());
  do {
    finish ateach (z in D_Base)
      for (p in D | here)
        Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;

    val delta =(A(D) – Temp(D)).lift(Math.abs).reduce(Math.max, 0.0);
    A(D) = Temp(D);
  } while (delta > epsilon);
}
```

- *Flat parallelism*: Assume one activity per place is desired.
- D.places() returns ValRail of places in D.
  - Dist.makeUnique(D.places()) returns a unique distribution (one point per place) over the given ValRail of places
- D | x returns sub-region of D at place x.

Explicit Loop Chunking

Heat Transfer in X10 – III

```
def run() {
  val D_Base = Dist.makeUnique(D.places());
  val blocks = DistUtil.block(D, P);
  do {
    finish ateach (z in D_Base)
      foreach (q in 1..P)
        for (p in blocks(here,q))
          Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;

    val delta =(A(D)-Temp(D)).lift(Math.abs).reduce(Math.max, 0.0);
    A(D) = Temp(D);
  } while (delta > epsilon);
}
```

- *Hierarchical parallelism*: P activities at place x.
  - Easy to change above code so P can vary with x.
- DistUtil.block(D,P)(x,q) is the region allocated to the q'th activity in place x. (Block-block division.)

Explicit Loop Chunking with Hierarchical Parallelism

Heat Transfer in X10 – IV

```
def run() {
  finish async {
    val c = clock.make();
    val D_Base = Dist.makeUnique(D.places());
    val diff = Array.make[Real](D_Base),
        scratch = Array.make[Real](D_Base);
    ateach (z in D_Base) clocked(c)
      do {
        diff(z) = 0.0D;
        for (p in D | here) {
          Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;
          diff(z) = Math.max(diff(z), Math.abs(A(p) - Temp(p)));
        }
        next;
        A(D | here) = Temp(D | here);
        reduceMax(z, diff, scratch);
      } while (diff(z) > epsilon);
}
}
```

One activity per place == MPI task

Akin to UPC barrier

- reduceMax() performs an all-to-all max reduction.

SPMD with all-to-all reduction == MPI style

Heat Transfer in X10 – V

```
def run() {
  finish async {
    val c = clock.make();
    val D_Base = Dist.makeUnique(D.places());
    val diff = Array.make[Real](D_Base),
        scratch = Array.make[Real](D_Base);
    ateach (z in D_Base) clocked(c)
      foreach (q in 1..P) clocked(c)
        do {
          if (q==1) diff(z) = 0.0D;
          var myDiff: Real = 0.0D;
          for (p in blocks(here,q)) {
            Temp(p) = A(p.stencil(1)).reduce(Double.+, 0.0)/4;
            myDiff = Math.max(myDiff, Math.abs(A(p) - Temp(p)));
          }
          atomic diff(z) = Math.max(myDiff, diff(z));
          next;
          A(blocks(here,q)) = Temp(blocks(here,q));
          if (q==1) reduceMax(z, diff, scratch);
          next;
        } while (diff(z) > epsilon);
} }
```

“OpenMP within MPI style”

Heat Transfer in X10 – VI

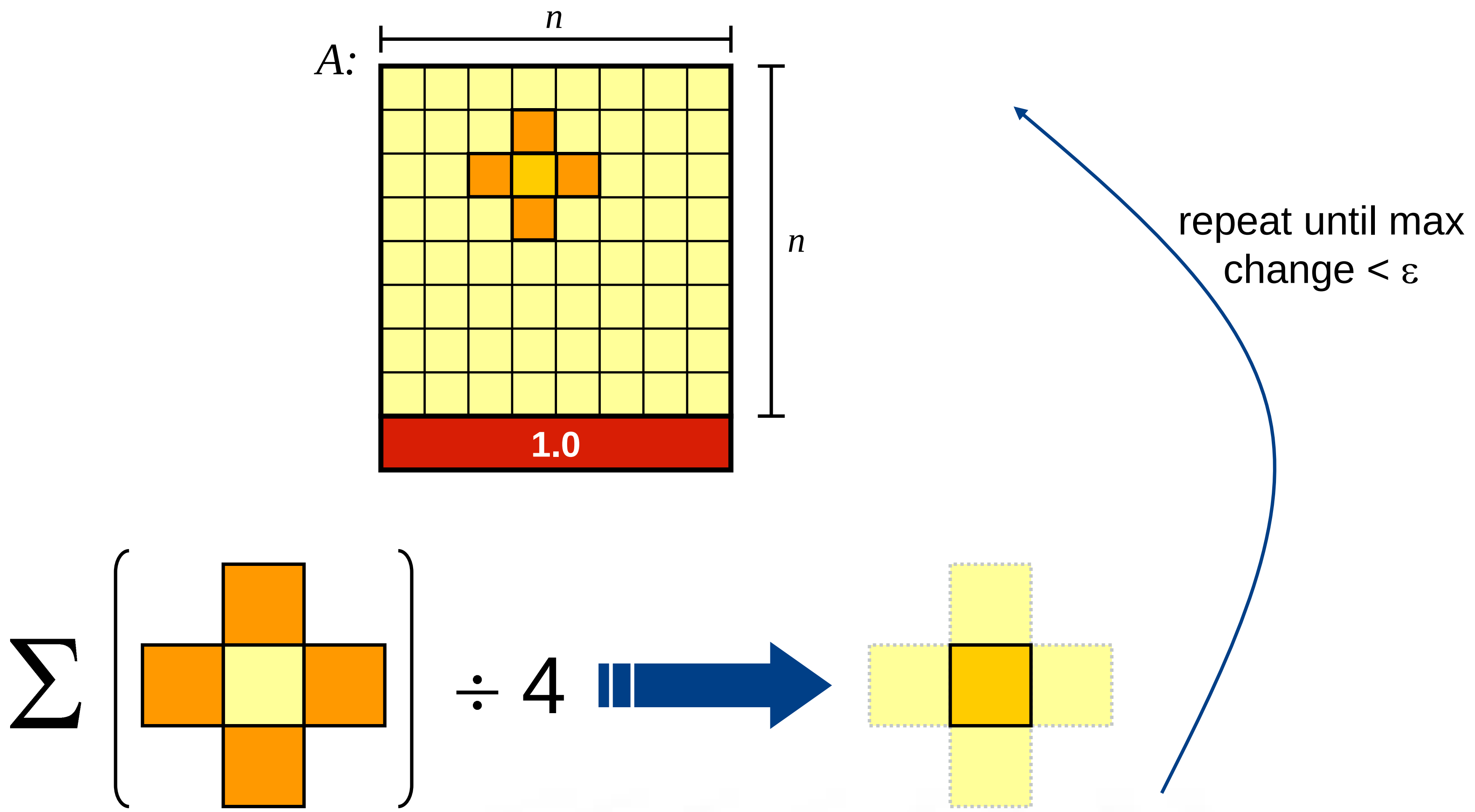
- All previous versions permit fine-grained remote access
  - Used to access boundary elements
- Much more efficient to transfer boundary elements in bulk between clock phases.
- May be done by allocating extra “ghost” boundary at each place
  - API extension: Dist.makeBlock(D, P, f)
    - D: distribution, P: processor grid, f: region$\rightarrow$region transformer
- reduceMax() phase overlapped with ghost distribution phase

Comparison of Languages

Chapel

Heat Transfer in Chapel

Heat Transfer in Pictures



Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [(i,j) in D] Temp(i,j) = (A(i-1,j) + A(i+1,j)
                          + A(i,j-1) + A(i,j+1)) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
             D: subdomain(BigD) = [1..n, 1..n],
       LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[Las

do {
  [(i



  con
  A[D
} whi

writeln(A);
```

Declare program parameters

const ⇒ can't change values after initialization

config ⇒ can be set on executable command-line

prompt> `jacobi --n=10000 --epsilon=0.0001`

note that no types are given; inferred from initializer

n ⇒ **integer** (current default, 32 bits)

epsilon ⇒ **floating-point** (current default, 64 bits)

Heat Transfer in Chapel

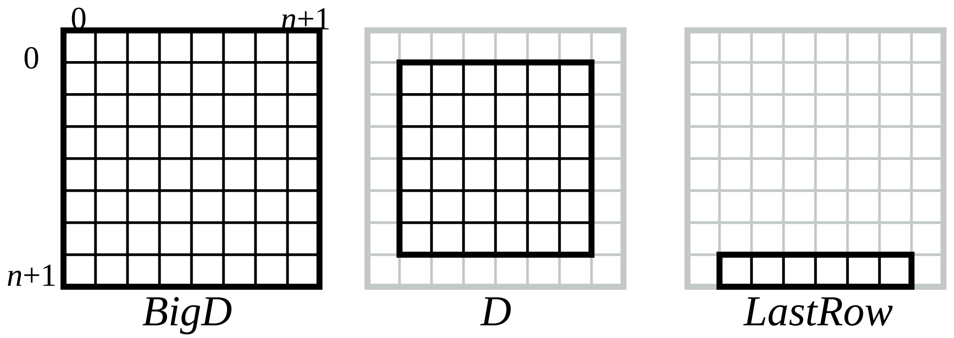
```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);
```

4;

Declare domains (first class index sets)

domain(2) ⇒ 2D arithmetic domain, indices are integer 2-tuples

subdomain(*P*) ⇒ a domain of the same type as *P* whose indices are guaranteed to be a subset of *P*'s



exterior ⇒ one of several built-in domain generators

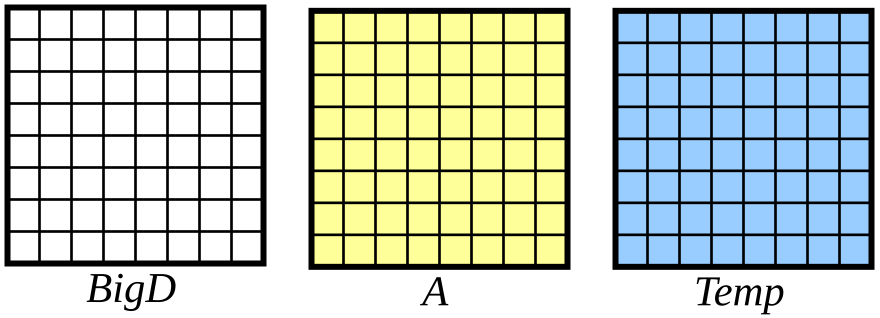
Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;
```

4;

Declare arrays

var ⇒ can be modified throughout its lifetime
: *T* ⇒ declares variable to be of type *T*
: *[D] T* ⇒ array of size *D* with elements of type *T*
(no initializer) ⇒ values initialized to default value (0.0 for reals)

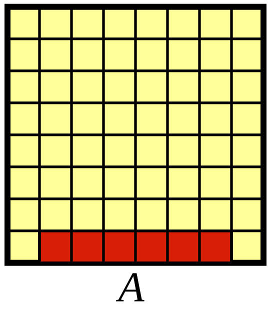


Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
               D: subdomain(BigD) = [1..n, 1..n],
         LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;
```

Set Explicit Boundary Condition

indexing by domain ⇒ slicing mechanism
array expressions ⇒ parallel evaluation

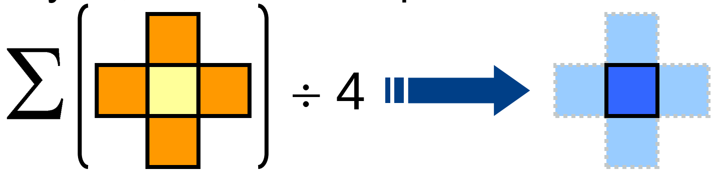


Heat Transfer in Chapel

Compute 5-point stencil

[(*i,j*) in *D*] $\Rightarrow$ parallel forall expression over *D*'s indices, binding them to new variables *i* and *j*

Note: since (*i,j*) $\in$ *D* and *D* $\subseteq$ *BigD* and *Temp*: [*BigD*]
$\Rightarrow$ no bounds check required for *Temp(i,j)*
with compiler analysis, same can be proven for A's accesses



```
    [(i,j) in D] Temp(i,j) = (A(i-1,j) + A(i+1,j)
                            + A(i,j-1) + A(i,j+1)) / 4;

    const delta = max reduce abs(A[D] - Temp[D]);
    A[D] = Temp[D];
  } while (delta > epsilon);

  writeln(A);
```

Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
```

Compute maximum change

***op* reduce** ⇒ collapse aggregate expression to scalar using *op*

Promotion: *abs()* and – are scalar operators, automatically promoted to work with array operands

```
do {
  [(i,j) in D] Temp(i,j) = (A(i-1,j) + A(i+1,j)
                          + A(i,j-1) + A(i,j+1)) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var

A[La

do {
  [(i,j) in D] Temp(i,j) = (A(i-1,j) + A(i+1,j)
                          + A(i,j-1) + A(i,j+1)) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Copy data back & Repeat until done

uses slicing and whole array assignment
standard *do…while* loop construct

Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1],
            D: subdomain(BigD) = [1..n, 1..n],
      LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [(                                           j)
                                               1)) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

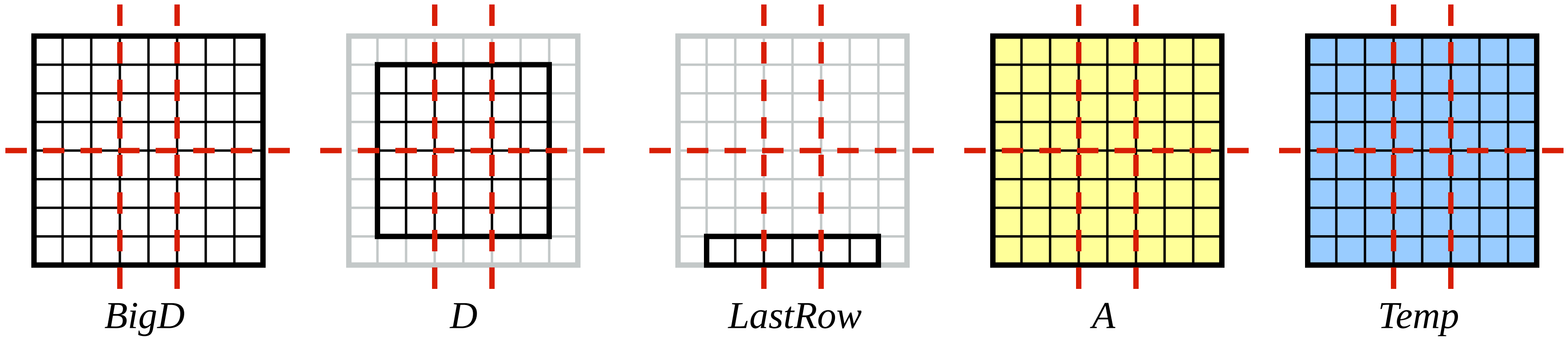
Write array to console

If written to a file, parallel I/O would be used

Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1] distributed Block,
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;
```

With this change, same code runs in a distributed manner
Domain distribution maps indices to *locales*
    ⇒ decomposition of arrays & default location of iterations over locales
    Subdomains inherit parent domain's distribution



Heat Transfer in Chapel

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1] distributed Block,
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [(i,j) in D] Temp(i,j) = (A(i-1,j) + A(i+1,j)
                          + A(i,j-1) + A(i,j+1)) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Heat Transfer in Chapel (Variations)

Heat Transfer in Chapel (double buffered version)

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1] distributed Block,
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

var A : [1..2] [BigD] real;

A[..][LastRow] = 1.0;

var src = 1, dst = 2;

do {
  [(i,j) in D] A(dst)(i,j) = (A(src)(i-1,j) + A(src)(i+1,j)
                            + A(src)(i,j-1) + A(src)(i,j+1)) / 4;

  const delta = max reduce abs(A[src] - A[dst]);
  src <=> dst;
} while (delta > epsilon);

writeln(A);
```

Heat Transfer in Chapel (named direction version)

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1] distributed Block,
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

const north = (-1,0), south = (1,0), east = (0,1), west = (0,-1);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [ind in D] Temp(ind) = (A(ind + north) + A(ind + south)
                        + A(ind + east)  + A(ind + west)) / 4;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Heat Transfer in Chapel (array of offsets version)

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1] distributed Block,
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

param offset : [1..4] (int, int) = ((-1,0), (1,0), (0,1), (0,-1));

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [ind in D] Temp(ind) = (+ reduce [off in offset] A(ind + off))
                        / offset.numElements;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Heat Transfer in Chapel (sparse offsets version)

```
config const n = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..n+1, 0..n+1] distributed Block,
         D: subdomain(BigD) = [1..n, 1..n],
   LastRow: subdomain(BigD) = D.exterior(1,0);

param stencilSpace: domain(2) = [-1..1, -1..1],
      offSet: sparse subdomain(stencilSpace)
             = ((-1,0), (1,0), (0,1), (0,-1));
var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
  [ind in D] Temp(ind) = (+ reduce [off in offSet] A(ind + off))
                          / offSet.numIndices;

  const delta = max reduce abs(A[D] - Temp[D]);
  A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Heat Transfer in Chapel (UPC-ish version)

```
config const N = 6,
             epsilon = 1.0e-5;

const BigD: domain(2) = [0..#N, 0..#N] distributed Block,
         D: subdomain(BigD) = D.expand(-1);

var grids : [0..1] [BigD] real;
var sg = 0, dg = 1;

do {
  [(x,y) in D] grids(dst)(x,y) = (grids(src)(x-1,y)
                                + grids(src)(x+1,y)
                                + grids(src)(x,y-1)
                                + grids(src)(x,y+1)) / 4;

  const dTmax = max reduce abs(grids(src) - grids(dst));
  src <=> dst;
} while (dTmax > epsilon);

writeln(A);
```

Comparison of Languages

Comparative Feature Matrix

Features Matrix

	UPC	X10	Chapel
Memory model	PGAS		
Programming/Execution model	SPMD	Multithreaded	Global-view / Multithreaded
Base Language	C	Java	N/A (influences include C, Modula, Java, Perl, CLU, ZPL, MTA, Scala, …)
Nested Parallelism	Not supported	Supported	Supported
Incremental Parallelization of code	Indirectly supported	Supported	Supported
Locality Awareness	Yes (Blocking and affinity)	Yes	Yes (affinity of code and data to locales; distributed data aggregates)
Dynamic Parallelism	Still in research	Yes – Asynchronous PGAS	Yes – Asynchronous PGAS

Features Matrix

	UPC	X10	Chapel
Implicit/Explicit Communications	Both	Both	Implicit; User can assert locality of a code block (checked at compile-/runtime)
Collective Operations	No explicit collective operations but remote string functions are provided	Yes (possibly nonblocking, initiated by single activity)	Reductions, scans, whole-array operations
Work Sharing	Different affinity values in upc_forall	Work-stealing supported on a single node.	Currently, must be explicitly done by the user; future versions will support a work-sharing mode
Data Distribution	Block, round-robin	Standard distributions, users may define more.	Library of standard distributions + ability for advanced users to define their own
Memory Consistency Model Control	Strict and relaxed allowed on block statements or variable by variable basis	Under development. (See theory in PPoPP 07)	Strict with respect to sync/single variables; relaxed otherwise

Features Matrix

	UPC	X10	Chapel
Dynamic Memory Allocation	Private or shared with or without blocking	Supports objects and arrays.	No pointers -- all dynamic allocations are through objects & array resizing
Synchronization	Barriers, split phase barrier, locks, and memory consistency control	Conditional atomic blocks, dynamic barriers (clocks)	Synchronization and single variables; transactional memory-style atomic blocks
Type Conversion	C rules Casting of shared pointers to private pointers	Coercions, conversions supported as in OO languages	C#-style rules plus explicit conversions
Pointers To Shared Space	Yes	Yes	Yes
global-view distributed arrays	Yes, but 1D only	Yes	Yes

Partial Construct Comparison

Constructs	UPC	X10	Chapel
Parallel loops	upc_forall	foreach, ateach	forall, coforall
Concurrency spawn	N/A	async,future,	begin, cobegin,
Termination detection	N/A	finish	sync
Distribution construct	affinity in upc_forall, blocksize in work distribution	places, regions, distributions	locales, domains, distributions
Atomicity control	N/A	Basic atomic blocks	TM-based atomic blocks
Data-flow synchronization	N/A	Conditional atomic blocks	single variables
Barriers	upc_barrier	clocks	sync variables

You might consider using UPC if...

- you prefer C-based languages
- the SPMD programming/execution model fits your algorithm
- 1D block-cyclic/cyclic global arrays fit your algorithm
- you need to do production work today

You might consider using X10 if...

- you prefer Java-style languages
- you require dynamic/nested parallelism than SPMD
- you require multidimensional global arrays
- you're able to work with an emerging technology

You might consider using Chapel if...

- you're not particularly tied to any base language
- you require dynamic/nested parallelism than SPMD
- you require multidimensional global arrays
- you're able to work with an emerging technology

Discussion

Overview

A. Introduction to PGAS (~ 30 mts)

B. Introduction to Languages
   A. UPC (~ 65 mts)
   B. X10 (~ 65 mts)
   C. Chapel (~ 65 mts)

C. Comparison of Languages (~45 minutes)
   A. Comparative Heat transfer Example
   B. Comparative Summary of features
   C. Discussion

D. **Hands-On (90 mts)**

D. Hands-On