Chapel: Data Parallelism
Data Parallelism:
- parallelism is driven by collections of data
  - data aggregates (arrays)
  - sets of indices (ranges, domains)
  - other user-defined collections
- e.g., “for all elements in array A ...”

Task Parallelism:
- parallelism is expressed in terms of distinct computations
- e.g., “create a task to do foo() while another does bar()”

(Of course, data parallelism is executed using tasks and task parallelism typically operates on data, so the line can get fuzzy at times...)
"Hello World" in Chapel: a Data Parallel Version

- Data Parallel Hello World

```chapel
config const numIters = 100000;

forall i in 1..numIters do
  writeln("Hello, world! ",
          "from iteration ", i,
          " of ", numIters);
```
Outline

- Domains and Arrays
  - Rectangular Domains and Arrays
  - Iterations and Operations
- Other Domain Types
- Reductions and Scans
- Jacobi Iteration Example
Domains

**Domain:** A first-class index set

- A fundamental Chapel concept for data parallelism
- Domains may optionally be distributed
config const m = 4, n = 8;

var D: domain(2) = {1..m, 1..n};
config const  \( m = 4, \ n = 8; \)

var  \( D: \text{domain}(2) = \{1..m, 1..n\}; \)

var  \( \text{Inner}: \text{subdomain}(D) = \{2..m-1, 2..n-1\}; \)
Domains Define Arrays

- **Syntax**

  ```
  array-type:
  [ domain-expr ] elt-type
  ```

- **Semantics**
  - Stores an `elt-type` for each index in `domain-expr`

- **Example**

  ```
  var A, B: [D] real;
  ```

- **Earlier example, revisited**

  ```
  var A: [1..3, 1..5] real; // [1..3, 1..5] creates an anonymous domain
  ```
Domain Iteration

- For loops (discussed already)
  - Execute loop body once per domain index, serially
    
    ```
    for i in Inner do ...
    ```

- Forall loops
  - Executes loop body once per domain index, in parallel
  - Loop must be *serializable* (executable by one task)
    
    ```
    forall i in Inner do ...
    ```

- Loop variables take on `const` domain index values
For all loops also support...

- A shorthand notation:

\[
[(i,j) \ \text{in} \ D] \ A[i,j] = i + j/10.0;
\]

- Expression-based forms:

\[
A = \text{forall} \ (i,j) \ \text{in} \ D \ \text{do} \ i + j/10.0;
\]

\[
A = [(i,j) \ \text{in} \ D] \ i + j/10.0;
\]
Domain values support...

- **Methods for creating new domains**
  
  ```javascript
  var D2 = Inner.expand(1, 0);
  ```

- **Intersection via Slicing**
  
  ```javascript
  var D3 = Inner.translate(0, 1);
  ```

- **Range operators (e.g., #, by, align)**

```javascript
var D4 = D2[D3];
```
Indexing into arrays with domain values results in a sub-array expression (an “array slice”)

\[
A[\text{Inner}] = B[\text{Inner}.\text{translate}(0,1)];
\]

\[
\begin{array}{c}
A \\
\end{array}
\begin{array}{c}
= \\
B
\end{array}
\]
Array Reallocation

Reassigning a domain logically reallocates its arrays
- array values are preserved for common indices

\[ D = \{1..2m, 1..2n\}; \]
Array Iteration

- Array expressions also support for and forall loops

```
for a in A[Inner] do ...
```

```
forall a in A[Inner] do ...
```

- Array loop indices refer to array elements (can be modified)

```
forall (a, (i,j)) in zip(A, D) do a = i + j/10.0;
```

Note that forall loops support zippered iteration, like for-loops.
Array Indexing

- Arrays can be indexed using variables of their domain’s index type (tuples) or lists of integers

```plaintext
var i = 1, j = 2;
var ij = (i, j);
A[ij] = 1.0;
A[i, j] = 2.0;
```

- Array indexing can use either parentheses or brackets

```plaintext
A(ij) = 3.0;
A(i, j) = 4.0;
```
Arrays are passed by reference by default

```chapel
proc zero(X: []) { X = 0; }
zero(A[Inner]); // zeroes the inner values of A
```

Formal array arguments can reindex actuals

```chapel
proc f(X: [1..b,1..b]) { ... } // X uses 1-based indices
f(A[lo..#b, lo..#b]);
```

Array alias declarations provide similar functionality

```chapel
var InnerA => A[Inner];
var InnerA1: [1..n-2,1..m-2] => A[2..n-1,2..m-1];
```
Promoting Functions and Operators

Functions/operators expecting scalars can also take...

...arrays, causing each element to be passed in

\[
\begin{align*}
\sin(A) & \approx \text{forall } a \text{ in } A \text{ do } \sin(a) \\
2*A & \approx \text{forall } a \text{ in } A \text{ do } 2*a
\end{align*}
\]

...domains, causing each index to be passed in

\[
\begin{align*}
\text{foo(Inner)} & \approx \text{forall } i \text{ in } \text{Inner} \text{ do } \text{foo}(i)
\end{align*}
\]

Multiple arguments promote using zippered iteration

\[
\begin{align*}
\text{pow}(A, B) & \approx \text{forall } (a,b) \text{ in } \text{zip}(A,B) \text{ do } \text{pow}(a,b)
\end{align*}
\]
Data Parallelism is Implicit

- forall loops are implemented using multiple tasks
  - ditto for operations that are equivalent to foralls
  - details depend on what is being iterated over

- many times, this parallelism can seem invisible
  - for this reason, Chapel’s data parallelism can be considered *implicitly parallel*
  - it also tends to make the data parallel features easier to use and less likely to result in bugs as compared to explicit tasks
By default*, controlled by three config variables:

--dataParTasksPerLocale=#
  • Specify # of tasks to execute for all loops
  • *Current Default:* number of processor cores

--dataParIgnoreRunningTasks=[true | false]
  • If false, reduce # of for all tasks by # of running tasks
  • *Current Default:* true

--dataParMinGranularity=#
  • If > 0, reduce # of for all tasks if any task has fewer iterations
  • *Current Default:* 1

*Default values can be overridden for specific domains/arrays
Outline

- Domains and Arrays
- Other Domain Types
  - Strided
  - Sparse
  - Associative
  - Opaque
- Reductions and Scans
- Jacobi Iteration Example
Chapel Domain Types

Chapel supports several domain types...

```chapel
var OceanSpace = {0..#lat, 0..#long},
AirSpace = OceanSpace by (2,4),
IceSpace: sparse subdomain(OceanSpace) = genCaps();
```

```
var Vertices: domain(opaque) = ..., People: domain(string) = ...
```
All domain types can be used to declare arrays...

```chapel
var Ocean: [OceanSpace] real,
    Air: [AirSpace] real,
    IceCaps[IceSpace] real;
```

```chapel
var Weight: [Vertices] real,
    Age: [People] int;
```
...to iterate over index sets...

forall $ij$ in AirSpace do
Ocean[$ij$] += IceCaps[$ij$];

forall $v$ in Vertices do
Weight[$v$] = numEdges[$v$];

forall $p$ in People do
Age[$p$] += 1;
Slicing

...to slice arrays...

Ocean[AirSpace] += IceCaps[AirSpace];

...Vertices[Interior]...      ...People[Interns]...

“steve”
“lee”
“sung”
“david”
“jacob”
“albert”
“brad”
Reallocation

...and to reallocate arrays

\[
\text{AirSpace} = \text{OceanSpace by } (2,2); \\
\text{IceSpace} += \text{genEquator}();
\]

```
newnode = Vertices.create();  
People += “vass”;
```
### Associative Domains and Arrays by Example

```plaintext
var Presidents: domain(string) =
    {"George", "John", "Thomas", "James", "Andrew", "Martin"};

Presidents += "William";

var Age: [Presidents] int,
    Birthday: [Presidents] string;

Birthday["George"] = "Feb 22";

forall president in President do
    if Birthday[president] == today then
        Age[president] += 1;
```

<table>
<thead>
<tr>
<th>Presidents</th>
<th>Birthday</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>George</td>
<td>Feb 22</td>
<td>277</td>
</tr>
<tr>
<td>John</td>
<td>Oct 30</td>
<td>274</td>
</tr>
<tr>
<td>Thomas</td>
<td>Apr 13</td>
<td>266</td>
</tr>
<tr>
<td>James</td>
<td>Mar 16</td>
<td>251</td>
</tr>
<tr>
<td>Andrew</td>
<td>Mar 15</td>
<td>242</td>
</tr>
<tr>
<td>Martin</td>
<td>Dec 5</td>
<td>227</td>
</tr>
<tr>
<td>William</td>
<td>Feb 9</td>
<td>236</td>
</tr>
</tbody>
</table>
Outline

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- Other Domain Types
- Reductions and Scans
- Jacobi Iteration Example
Reductions

• Syntax

\[
\text{reduce-expr:} \\
\text{reduce-op reduce iterator-expr}
\]

• Semantics

• Combines argument values using \textit{reduce-op}

• \textit{Reduce-op} may be built-in or user-defined

• Examples

\begin{verbatim}
total = + reduce A;
bigDiff = max reduce [i in Inner] abs(A[i]-B[i]);
(minVal, minLoc) = minloc reduce zip(A, D);
\end{verbatim}
Scans

• **Syntax**

```
scan-expr:
  scan-op scan iterator-expr
```

• **Semantics**
  • Computes parallel prefix over values using `scan-op`
  • *Scan-op* may be any *reduce-op*

• **Examples**

```plaintext
var A, B, C: [1..5] int;
A = 1;                   // A:  1  1  1  1  1
B = + scan A;            // B:  1  2  3  4  5
C = min scan B;          // C:  1  1 -3 -3 -3
```
Reduction and Scan Operators

• Built-in
  • +, *, &&, ||, &, |, ^, min, max
  • minloc, maxloc
    • Takes a zipped pair of values and indices
    • Generates a tuple of the min/max value and its index

• User-defined
  • Defined via a class that implements a standard interface
  • Compiler generates code that calls these methods
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Jacobi Iteration in Pictures

\[ A : \sum_{i=1}^{n} \frac{1.0}{4} \text{ until max change } < \epsilon \]
Jacobi Iteration in Chapel

```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 {
        + 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);
```
Jacobi Iteration 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)) / 4.0;
    const delta = max reduce abs(A(D) - Temp(D));
    A[D] = Temp[D];
} while (delta > epsilon);
writeln(A);
```

Declare program parameters

- `config` ⇒ can be set on executable command-line
  ```
prompt> jacobi --n=10000 --epsilon=0.0001
  ```
- `const` ⇒ can’t change values after initialization
- `var` ⇒ declaration type inferred from initializer

Note that no types are given; inferred from initializer
- `n` ⇒ default integer (32 bits)
- `epsilon` ⇒ default real floating-point (64 bits)
Jacobi Iteration in Chapel

```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;
    var delta = max reduce abs(A(D) - Temp(D));
    A(D) = Temp(D);
} while (delta > epsilon);
write (A);
```

**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 indices
- **exterior** ⇒ one of several built-in domain generators
Jacobi Iteration in Chapel

```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;
```

Declare arrays

*var ⇒ can be modified throughout its lifetime
: [BigD] T ⇒ array of size BigD with elements of type T (no initializer) ⇒ values initialized to default value (0.0 for reals)*
Jacobi Iteration 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
Jacobi Iteration in Chapel

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

Compute 5-point stencil

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

\[
\sum \left( \begin{array}{c}
A \\
A \\
A \\
A \\
A \\
\end{array} \right) \div 4
\]

\[
[(i,j) \text{ in } D] \quad \text{Temp}[i,j] = (A[i-1,j] + A[i+1,j] \\
+ A[i,j-1] + A[i,j+1]) / 4;
\]

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

writeln(A);
Jacobi Iteration in Chapel

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

const BigD: domain(2) = {0..n+1, 0..n+1},

Compute maximum change

\textit{op reduce} \Rightarrow \text{collapse aggregate expression to scalar using } op

\textit{Promotion: abs()} and – are scalar operators, automatically promoted to
work with array operands

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

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

 writeln(A);```

Compute maximum change

\textit{op reduce} \Rightarrow \text{collapse aggregate expression to scalar using } op

\textit{Promotion: abs()} and – are scalar operators, automatically promoted to
work with array operands
Jacobi Iteration in Chapel

```chapel
config const n = 6,
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    D: subdomain(BigD) = {1..n, 1..n},
    LastRow: subdomain(BigD) = D.exterior(1,0);

var A, Temp : [BigD] real;
A[LastRow] = 1.0;

do {
        + 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
Jacobi Iteration in Chapel

```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 {
    + 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);
```

Write array to console
Jacobi Iteration in Chapel

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

const BigD = {0..n+1, 0..n+1} dmapped 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 mapping of iterations to locales

Subdomains inherit parent domain’s distribution
Jacobi Iteration in Chapel

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

const BigD = {0..n+1, 0..n+1} dmapped 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 {
                              + 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);
```
Data Parallelism: Status

- Most features implemented and working correctly
- Scalar performance not optimal for higher-dimensional domain/array operations
- Implementation of unstructured domains/arrays is correct but inefficient
Future Directions

- Gain more experience with unstructured (graph-based) domains and arrays
Questions?

- Domains and Arrays
  - Regular Domains and Arrays
  - Iterations and Operations
- Other Domain Types
  - Strided
  - Sparse
  - Associative
  - Opaque
- Data Parallel Operations
  - Reductions
  - Scans
- Jacobi Iteration Example