Data Parallelism
Domains

**Domain:**
- A first-class index set
- The fundamental Chapel concept for data parallelism

```chapel
config const m = 4, n = 8;
const D = {1..m, 1..n};
const Inner = {2..m-1, 2..n-1};
```
Domains

Domain:
- A first-class index set
- The fundamental Chapel concept for data parallelism
- Useful for declaring arrays and computing with them

```
config const m = 4, n = 8;

const D = {1..m, 1..n};
const Inner = {2..m-1, 2..n-1};

var A, B, C: [D] real;
```
Chapel Domain Types

- **dense**
- **strided**
- **sparse**
- **associative**
- **unstructured**

Chapel supports several types of domains (index sets):

- dense
- strided
- sparse
- associative
- unstructured
Chapel Array Types

- dense
- strided
- sparse

- associative
- unstructured
Data Parallelism By Example: STREAM Triad

```plaintext
const ProblemSpace = {1..m};

var A, B, C: [ProblemSpace] real;

forall (a,b,c) in zip(A,B,C) do
  a = b + alpha*c;
```

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Forall Loops

**Forall loops:** Central concept for data parallel computation

- Like for-loops, but parallel
- Implementation details determined by iterand (e.g., $D$ below)
  - specifies number of tasks, which tasks run which iterations, …
  - in practice, typically uses a number of tasks appropriate for target HW

```plaintext
forall (i,j) in D do
A[i,j] = i + j/10.0;
```

- **Forall loops assert…**
  - **parallel safety:** OK to execute iterations simultaneously
  - **order independence:** iterations could occur in any order
  - **serializability:** all iterations could be executed by one task
    - e.g., can’t have synchronization dependences between iterations
Comparison of Loops: For, Forall, and Coforall

**For loops:** executed using one task
- use when a loop must be executed serially
- or when one task is sufficient for performance

**Forall loops:** typically executed using $1 < \#\text{tasks} \ll \#\text{iters}$
- use when a loop *should* be executed in parallel…
- …but *can* legally be executed serially
- use when desired \# tasks $\ll$ \# of iterations

**Coforall loops:** executed using a task per iteration
- use when the loop iterations *must* be executed in parallel
- use when you want \# tasks $==$ \# of iterations
- use when each iteration has substantial work

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Forall Intents

● Tell how to “pass” variables from outer scopes to tasks
  ● Similar to argument intents in syntax and philosophy
    ● also adds a “reduce intent”, similar to OpenMP
  ● Design principles:
    ● ”principle of least surprise”
    ● avoid simple race conditions
    ● avoid copies of (potentially) expensive data structures
Forall Intent Examples: Scalars

```plaintext
var sum: real;
forall i in 1..n do // default intent of scalars is 'const in'
    sum += computeMyResult(i); // so this is illegal (and avoids a race)

var sum: real;
forall i in 1..n with (ref sum) do // override default intent
    sum += computeMyResult(i); // we’ve now requested a race

var sum: real;
forall i in 1..n with (+ reduce sum) do // override default intent
    sum += computeMyResult(i); // each task accumulates into its own copy
// on loop exit, all tasks combine their results into original ‘sum’
```
Forall Intent Examples: Arrays

```c
default intent for arrays is ‘ref’

```
const ProblemSpace = {1..m};

var A, B, C: [ProblemSpace] real;

forall (a,b,c) in zip(A,B,C) do
  a = b + alpha*c;
Data Parallelism By Example: STREAM Triad

```plaintext
const ProblemSpace = {1..m};

var A, B, C: [ProblemSpace] real;

A = B + alpha * C;  // equivalent to the previous zippered forall version
```
Function promotion

- **Scalar functions may be called with array arguments**
  - functions expecting arguments of type `t` can be passed array-of-`t`
  - results in data parallel invocation of function

```c
proc foo(x: int, y: int) {
    return 2*x + y;
}
writeln(foo(3,4)); // prints 10
writeln(foo([1, 2, 4], [2, 3, 4])); // prints 4 7 12
```

- Promotion is equivalent to zippered iteration:

```c
foo(A, B); == forall (a,b) in zip(A, B) do foo(a, b);
```

- **Ranges/domains can also promote functions:**

```c
writeln(foo(1..3, 1..6 by 2)); // prints 3 7 11
```
Implication of Zippered Promotion Semantics

Whole-array operations are implemented element-wise…

\[
A = B + \alpha \times C; \quad \Rightarrow \quad \text{forall } (a,b,c) \text{ in zip}(A,B,C) \text{ do } \\
a = b + \alpha \times c;
\]

…rather than operator-wise.

\[
A = B + \alpha \times C; \quad \Rightarrow \quad \text{forall } (a,b,c) \text{ in zip}(A,B,C) \text{ do } \\
T1 = \alpha \times C; \\
A = B + T1;
\]
Implication of Zippered Promotion Semantics

Whole-array operations are implemented element-wise...

\[
A = B + \alpha C; \quad \Rightarrow \quad \text{for all } (a,b,c) \text{ in } \text{zip}(A,B,C) \text{ do } a = b + \alpha c;
\]

⇒ No temporary arrays required by semantics
⇒ No surprises in memory requirements
⇒ Friendlier to cache utilization

⇒ Differs from traditional array language semantics

\[
A[D] = A[D-\text{one}] + A[D+\text{one}]; \quad \Rightarrow \quad \text{for all } (a1, a2, a3) \text{ in } (A[D], A[D-\text{one}], A[D+\text{one}]) \text{ do } a1 = a2 + a3;
\]

Read/write race!
Data Parallelism by Example: Jacobi Iteration

\[ A : \sum_{i=1}^{n} \frac{1}{4} \]

repeat until max change < \( \varepsilon \)
Jacobi Iteration in Chapel

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

const BigD = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

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

do {
    forall (i,j) in D do

    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 = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;
A[LastRow] = 1.0;
do {
    forall (i,j) in D do
    const delta = max reduce abs(A[D] - Temp[D]);
    A[D] = Temp[D];
} while (delta > epsilon);
writeln(A);
```

Declare domains (first class index sets)

{lo..hi, lo2..hi2} ⇒ 2D rectangular domain, with 2-tuple indices

Dom1[Dom2] ⇒ computes the intersection of two domains

.exterior() ⇒ one of several built-in domain generators
Jacobi Iteration in Chapel

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

const BigD = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

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

**Declare arrays**

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

config const n = 6,

Compute 5-point stencil

forall ind in Dom ⇒ parallel forall expression over Dom’s indices,
    binding them to ind
    (here, since Dom is 2D, we can de-tuple the indices)

\[
\sum \left( \begin{array}{ccc}
\ast & \ast & \ast \\
\ast & \ast & \ast \\
\ast & \ast & \ast
\end{array} \right) \div 4
\]

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 = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

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

do {
    forall (i,j) in D do
    const delta = max reduce abs(A[D] - Temp[D]);
    A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

Set Explicit Boundary Condition

`Arr[Dom] ⇒ refer to array slice ("forall i in Dom do ...Arr[i]...")`

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### Array Slicing

- **Domains can be used to index into arrays**
  - Can be thought of as “promoted array indexing”

\[
A[\text{InnerD}] = B[\text{InnerD}+(0,1)];
\]

- **Slices can also be expressed with ranges:**

\[
A[2..3, \ldots] = B[3.., 1..n];
\]
Rank Change Slicing

- **Slicing using a 1-element range preserves dimensionality**
  - This is a 2D array expression that’s 1 x n:

- **Slicing using a scalar results in a rank change**:
  - This is a 1D array expression of $n$ elements:
Jacobi Iteration in Chapel

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

Compute maximum change

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

**Promotion:** abs() and – are scalar operators; providing array operands
results in parallel evaluation equivalent to:

```chapel
forall (a,t) in zip(A,Temp) do abs(a - t)
```

do {
    forall (i,j) in D do

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

writeln(A);
```
Reductions in Chapel

- **Standard reductions supported by default:**
  
  
  - +, *, min, max, &, |, &&, ||, minloc, maxloc, ...
  
- **Reductions can reduce arbitrary iterable expressions:**
  
  ```
  const total = + reduce Arr,
  factN = * reduce 1..n,
  biggest = max reduce (for i in myIter() do foo(i));
  ```

- **Advanced users can write their own reductions**
  
  - However, note that the interface is still evolving
Jacobi Iteration in Chapel

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

const BigD = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

var A, Temp : [BigD]real;
A[LastRow] = 1.0;
do {
    forall (i,j) in D do
    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

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

const BigD = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

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

do {
    forall (i,j) in D do

    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 = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
    forall (i,j) in D do

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

writeln(A);

use BlockDist;
```
Jacobi Iteration in Chapel

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

const BigD = {0..n+1, 0..n+1},
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;
do {
    forall (i,j) in D do
    const delta = max reduce abs(A[D] - Temp[D]);
    A[D] = Temp[D];
} while (delta > epsilon);

writeln(A);
```

By default, domains and their arrays are mapped to a single locale. Any data parallelism over such domains/arrays will be executed by the cores on that locale. Thus, this is a shared-memory parallel program.
Jacobi Iteration in Chapel (distributed memory)

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

const BigD = {0..n+1, 0..n+1} dmapped Block({1..n, 1..n}),
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;
A[LastRow] = 1.0;
do {
    forall (i,j) in D do
    const delta = max reduce abs(A[D] - Temp[D]);
    A[D] = Temp[D];
} while (delta > epsilon);
writeln(A);
```

With these simple changes, we specify a mapping from the domains and arrays to locales. Domain maps describe the mapping of domain indices and array elements to locales. This specifies how array data is distributed across locales. It also specifies how iterations over domains/arrays are mapped to locales.
Jacobi Iteration in Chapel (distributed memory)

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

const BigD = {0..n+1, 0..n+1} dmapped Block({1..n, 1..n}),
    D = BigD[1..n, 1..n],
    LastRow = D.exterior(1,0);

var A, Temp : [BigD] real;

A[LastRow] = 1.0;

do {
    forall (i,j) in D do

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

writeln(A);

use BlockDist;
```
Questions about Data Parallelism?
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