Data Parallelism
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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

```chapel
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 Array Types

- dense
- strided
- sparse

- associative
- unstructured

All Chapel domain types support domain maps.
Data Parallelism By Example: STREAM Triad

\texttt{const} ProblemSpace = \{1..m\};

\texttt{var} A, B, C: [ProblemSpace] real;

\texttt{forall} (a,b,c) \texttt{in} \texttt{zip}\(A,B,C\) \texttt{do}
\texttt{a = b + alpha*c;}

\begin{align*}
\alpha \cdot &
\end{align*}
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
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

```
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

```plaintext
var sum: [1..1000] real;
forall i in 1..1000 do
    sum[i] = computeMyResult(i);           // default intent for arrays is ‘ref’
                                                    // (avoids array copies by default)

var sum: [1..1000] real;
forall i in 1..1000 with (in sum) do     // override default intent: “copy in”
    sum[i] = computeMyResult(i);           // each task has its own copy now

var sum: [1..1000] real;
forall i in 1..n with (+ reduce sum) do   // request reduce on exit
    sum[computeBucket(i)] += 1;          // each task has its own copy now
// on loop exit, tasks combine their results into original ‘sum’, computing a histogram
```
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

\[
\text{const ProblemSpace} = \{1..m\};
\]

\[
\text{var A, B, C: [ProblemSpace] real;}
\]

\[
A = B + \alpha \cdot C; \quad \text{// equivalent to the previous zippered forall version}
\]
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

```plaintext
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:

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

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

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

Whole-array operations are implemented element-wise…

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

…rather than operator-wise.

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

\[ T_1 = \alpha \times C; \]
\[ A = B + T_1; \]
Implication of Zippered Promotion Semantics

Whole-array operations are implemented element-wise…

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

\[ \Rightarrow \text{No temporary arrays required by semantics} \Rightarrow \text{No surprises in memory requirements} \Rightarrow \text{Friendlier to cache utilization} \]

\[ \Rightarrow \text{Differs from traditional array language semantics} \]

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

\[ \text{Read/write race!} \]
Data Parallelism by Example: Jacobi Iteration

\[ A: \sum_{\text{1.0}} \frac{n}{4} \text{repeat until max change } < \epsilon \]
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);
```
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

`A[j+1]) / 4;`

```cpp
int i, j;
for (i = 0; i < n+1; i++) {
    for (j = 0; j < n+1; j++) {
        A[i][j] = 0;
    }
}
```

`.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;

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 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

```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)

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

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);
```

Set Explicit Boundary Condition

Arr[Dom] ⇒ refer to array slice ("forall i in Dom do …Arr[i]…")
**Array Slicing**

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

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

  \[ A[2..3, ..] = B[3.., 1..n]; \quad = \]

- Slices can also be expressed with ranges:
Rank Change Slicing

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

```plaintext
...A[2..2, ..]...
```

- Slicing using a scalar results in a rank change:
  - This is a 1D array expression of \( n \) elements:

```plaintext
...A[2, ..]...
```
Jacobi Iteration in Chapel

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

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);
```

**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)
```

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Reductions in Chapel

- **Standard reductions supported by default:**
  
  +, *, min, max, &, |, &&, ||, minloc, maxloc, ...

- **Reductions can reduce arbitrary iterable expressions:**

  ```chapel
  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

```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

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

cost 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);
```

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},
    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);

use BlockDist;
```

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, specifies how array data is distributed across locales, and 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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