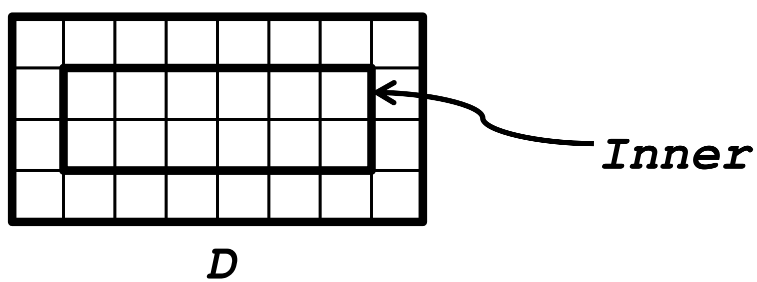
Data Parallelism

Domains

Domain:

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

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

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

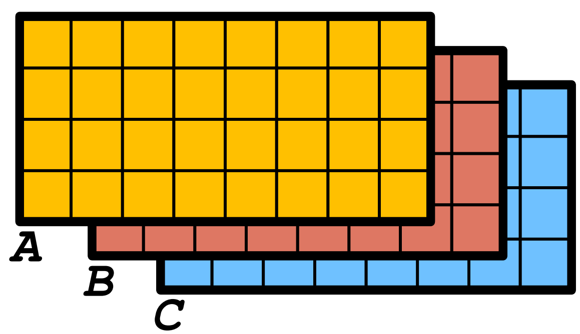


Domains

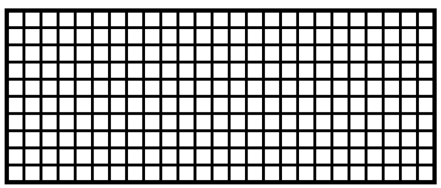
Domain:

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

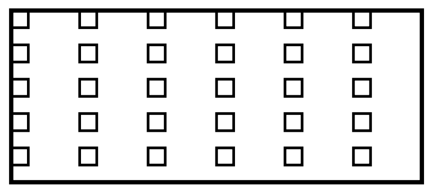
```
config const m = 4, n = 8;

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

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



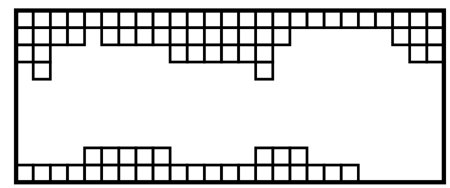
Chapel Domain Types



dense

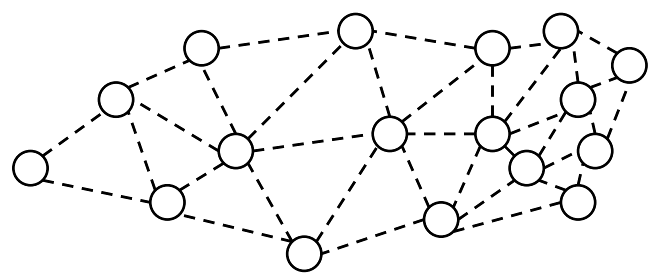


strided



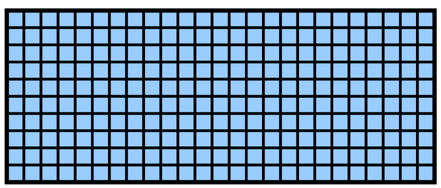
sparse

associative

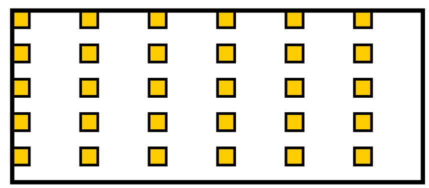


unstructured

Chapel Array Types



dense



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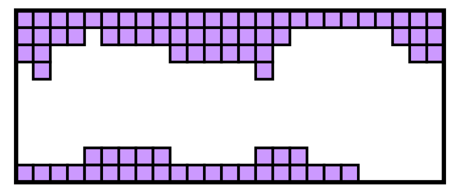
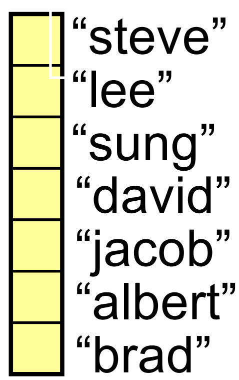
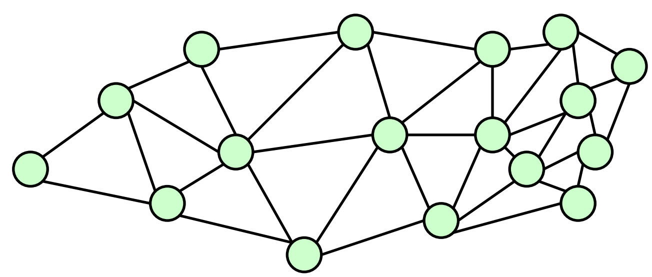


sparse



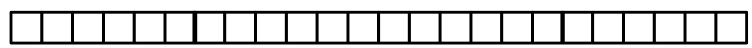
associative



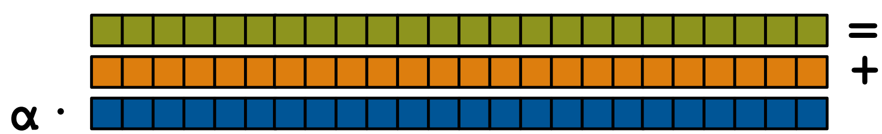
unstructured

Data Parallelism By Example: STREAM Triad

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



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




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

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

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

1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8

- **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 < #tasks << #iters

- use when a loop *should* be executed in parallel…
- …but *can* legally be executed serially
- use when desired # tasks << # 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

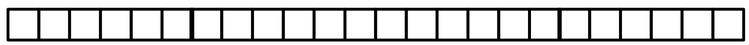
```
var sum: real;
forall i in 1..n do                  // default intent of scalars is 'const in'
  sum += computeMyResult(i);         // so this is illegal (and avoids a race)

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

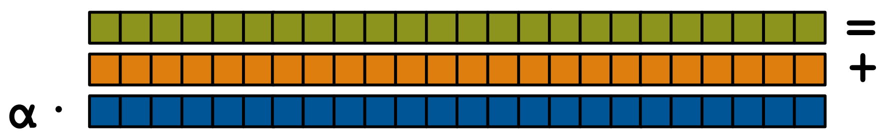
```
var sum: [1..1000] real;
forall i in 1..1000 do                   // default intent for arrays is 'ref'
  sum[i] = computeMyResult(i);           // (avoids array copies by default)

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
```

Data Parallelism By Example: STREAM Triad

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



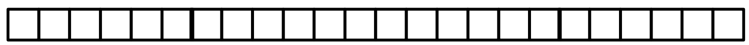
```
var A, B, C: [ProblemSpace] real;
```



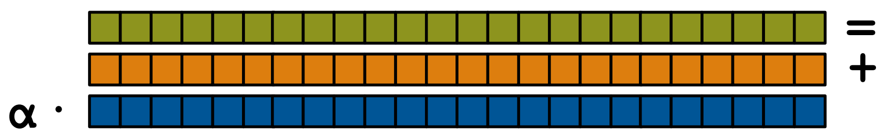

```
forall (a,b,c) in zip(A,B,C) do
  a = b + alpha*c;
```

Data Parallelism By Example: STREAM Triad

```
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

```
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:

```
foo(A, B);
```

==

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

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

```
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 * C;
```

⇒

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

…rather than operator-wise.

```
A = B + alpha * C;
```

$\not\Rightarrow$

```
T1 = alpha * C;
A = B + T1;
```

Implication of Zippered Promotion Semantics

Whole-array operations are implemented element-wise…

```
A = B + alpha * C;
```

⇒

```
forall (a,b,c) in zip(A,B,C) 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

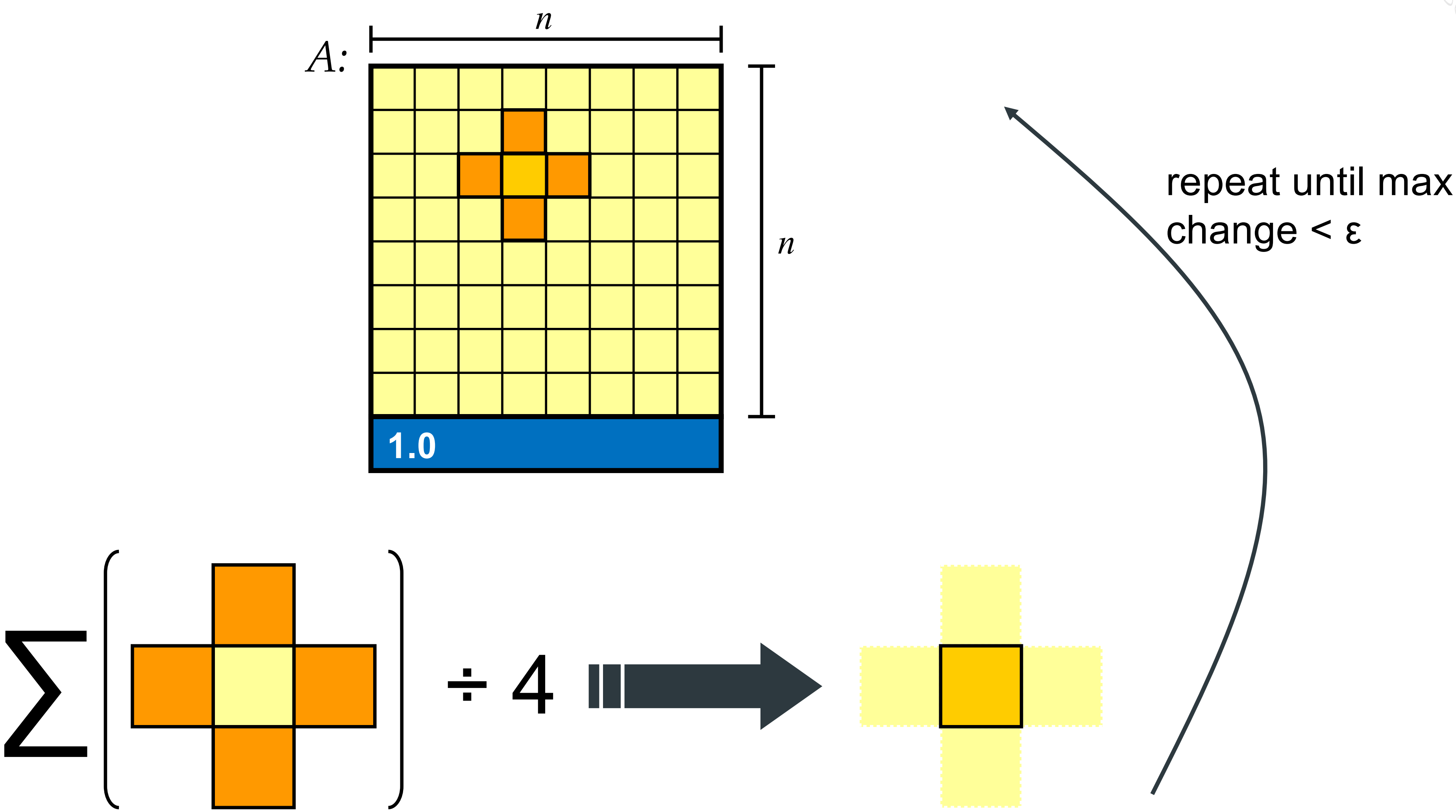
```
A[D] = A[D-one] + A[D+one];
```

⇒

```
forall (a1, a2, a3)
  in (A[D], A[D-one], A[D+one]) do
    a1 = a2 + a3;
```

Read/write race!

Data Parallelism by Example: Jacobi Iteration



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
    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);
```

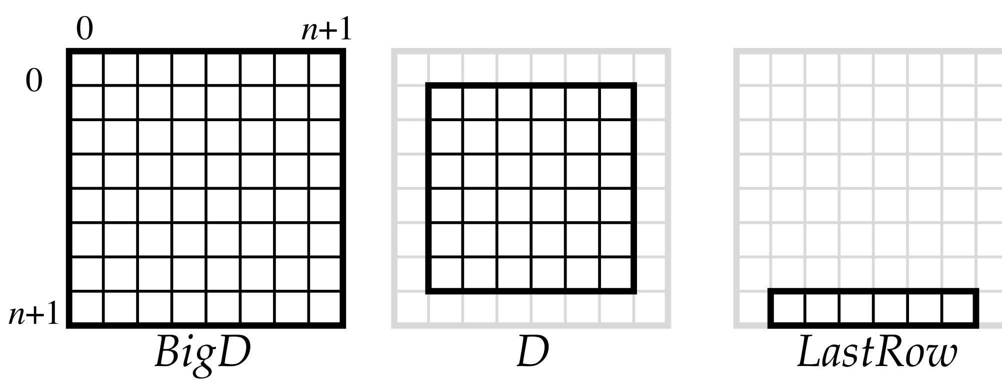
Jacobi Iteration in Chapel

```
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);

va

A[

do
                                                j+1]) / 4;

}

wr
```

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



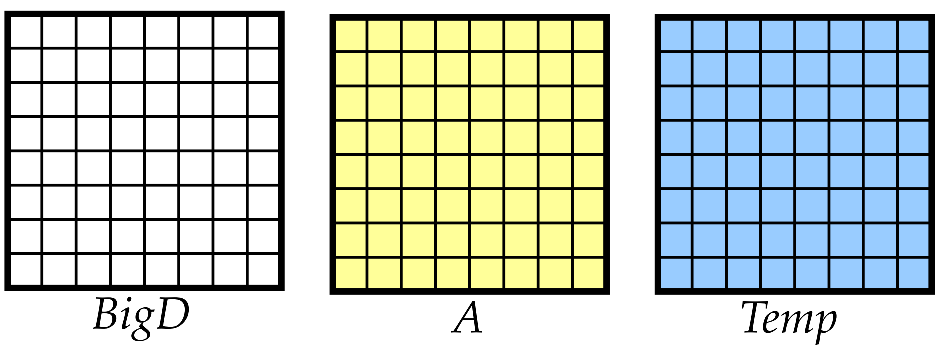
.exterior() ⇒ one of several built-in domain generators

Jacobi Iteration in Chapel

```
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)




```
[i,j+1]) / 4;
```

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)

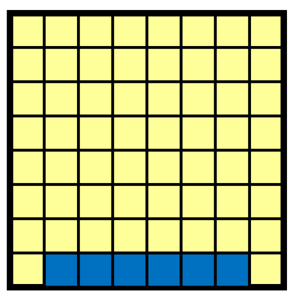

```
do {
  forall (i,j) in D do
    Temp[i,j] = (A[i-1,j] + A[i+1,j] + A[i,j-1] + A[i,j+1]) / 4;

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

writeln(A);
```

Jacobi Iteration in Chapel

```
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
                                                         j+1]) / 4;

}

wr
```

Set Explicit Boundary Condition

Arr[Dom] ⇒ refer to array slice (“forall i in Dom do …Arr[i]…”)

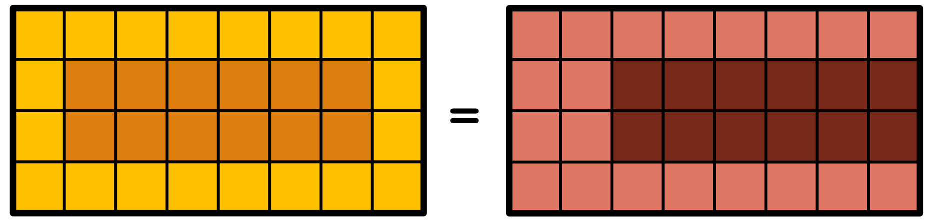


A

Array Slicing

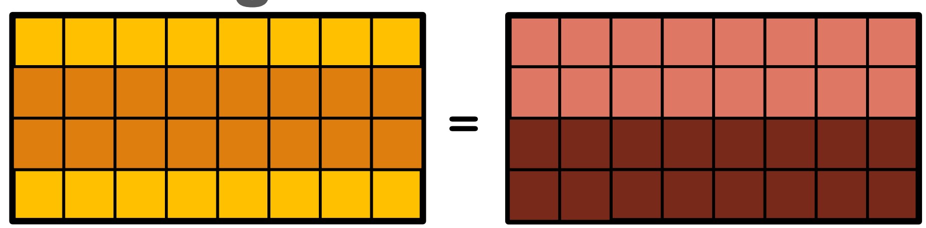
- **Domains can be used to index into arrays**
  - Can be thought of as "promoted array indexing"

```
A[InnerD] = B[InnerD+(0,1)];
```



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

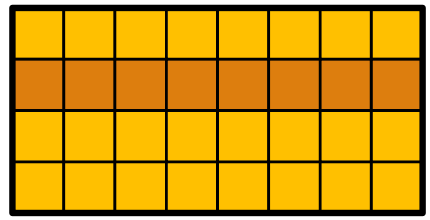
```
A[2..3, ..] = B[3.., 1..n];
```



Rank Change Slicing

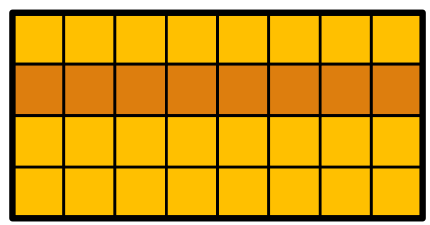
- **Slicing using a 1-element range preserves dimensionality**
  - This is a 2D array expression that's 1 x n:

```
…A[2..2, ..]…
```



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

```
…A[2, ..]…
```



Jacobi Iteration in 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:

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

```
do {
  forall (i,j) in D do
    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);
```

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],
```

Copy data back & Repeat until done

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

```
do {
  forall (i,j) in D do
    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

```
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
    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);
```

Write array to console

Jacobi Iteration in Chapel

```
config const n = 6,
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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
    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);

use BlockDist;
```

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;
```

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.

```
    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 (distributed memory)

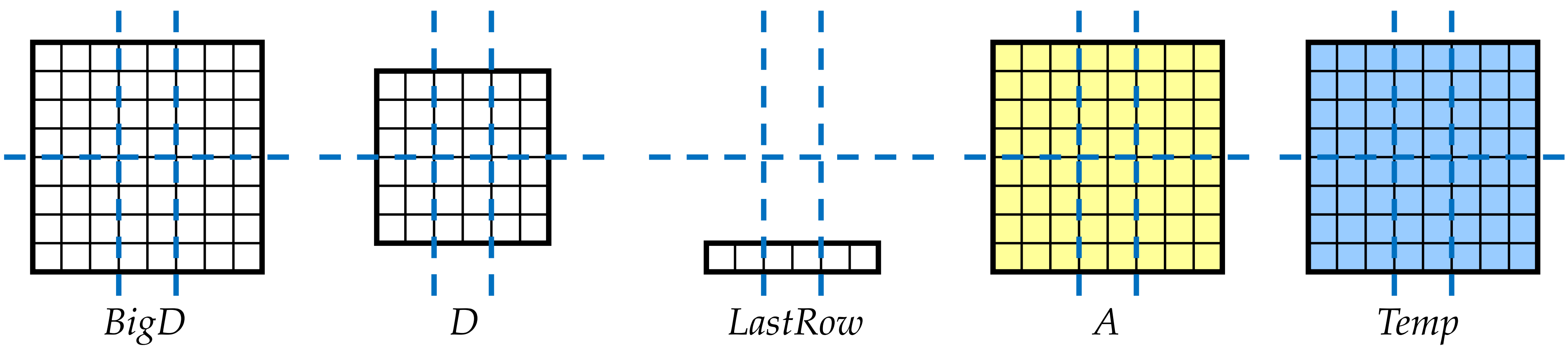
```
config const n = 6,
             epsilon = 1.0e-5;

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);
```

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

specifies how iterations over domains/arrays are mapped to locales




```
use BlockDist;
```

Jacobi Iteration in Chapel (distributed memory)

```
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
    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);

use BlockDist;
```

Questions about Data Parallelism?

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