Locality By Example

SC14
New Orleans, LA | hpc matters.

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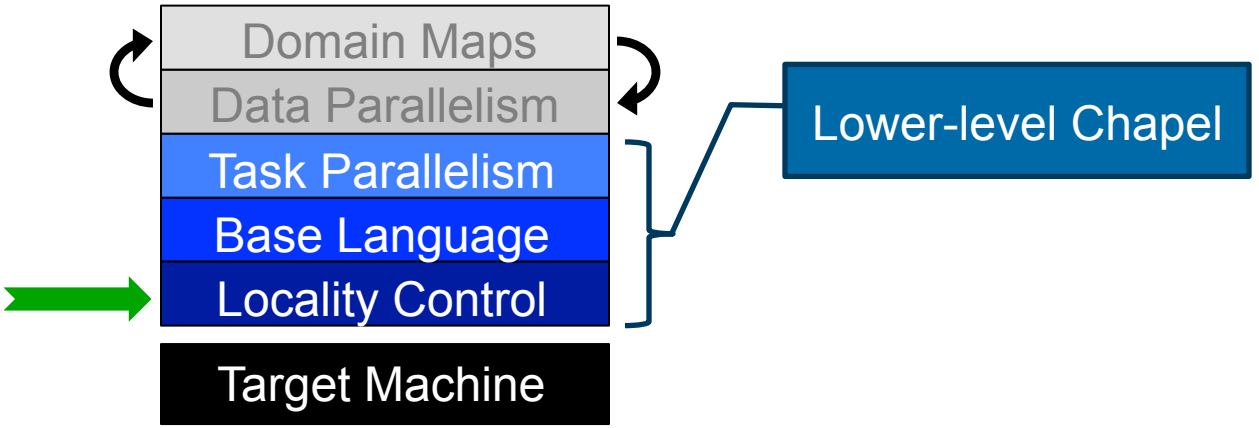
Locality Features



"Hello World" in Chapel: a Multi-Locale Version

- **Multi-locale Hello World**

```
coforall loc in Locales do
  on loc do
    writeln("Hello, world! ",
            "from node ", loc.id, " of ", numLocales);
```

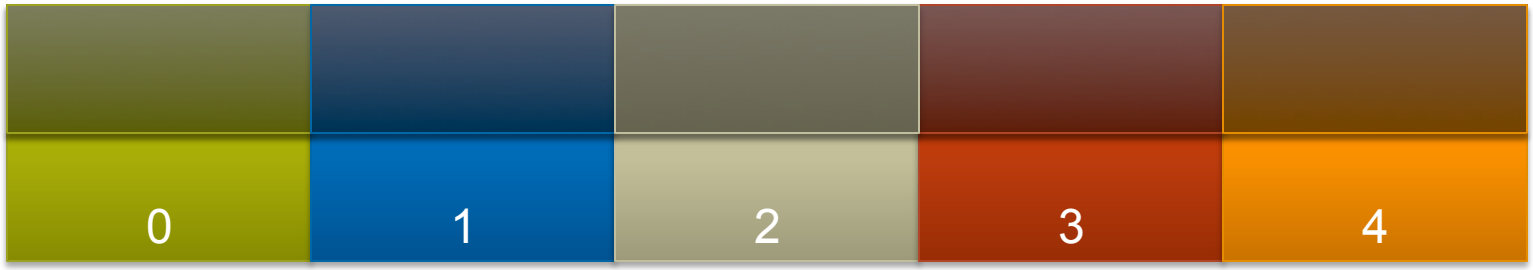
```
Hello, world! from node 3 of 6
Hello, world! from node 0 of 6
Hello, world! from node 5 of 6
Hello, world! from node 2 of 6
Hello, world! from node 1 of 6
Hello, world! from node 4 of 6
```

The Locale Type

Definition:

- Abstract unit of target architecture
- Supports reasoning about locality
  - defines “here vs. there” / “local vs. remote”
- Capable of running tasks and storing variables
  - i.e., has processors and memory

Typically: A compute node (multicore processor or SMP)



Locales (think: “compute nodes”)

Getting started with locales

- Specify # of locales when running Chapel programs

```
% a.out --numLocales=8
```

```
% a.out -nl 8
```

- Chapel provides built-in locale variables

```
config const numLocales: int = …;
const Locales: [0..#numLocales] locale = …;
```

- User's `main()` begins executing on locale #0

Locale Operations: System Queries

- Locale methods support queries about the target system:

```
proc locale.physicalMemory(…) { … }
proc locale.numCores { … }
proc locale.maxTaskPar { … }
proc locale.id { … }
proc locale.name { … }
```

```
const nodeMemory     = here.physicalMemory();
const systemMemory   = + reduce Locales.physicalMemory();
const maxNodeMemory = max reduce Locales.physicalMemory();
const minNodeMemory = min reduce Locales.physicalMemory();

if (minNodeMemory != maxNodeMemory) then
  writeln("My Locales have different amounts of memory");
```

Parallelism and Locality: Orthogonal in Chapel

- This is a **parallel**, but local program:

```
begin writeln("Hello world!");
writeln("Goodbye!");
```

- This is a **distributed**, but serial program:

```
writeln("Hello from locale 0!");
on Locales[1] do writeln("Hello from locale 1!");
writeln("Goodbye from locale 0!");
```

- This is a **distributed**, **parallel** program:

```
begin on Locales[1] do writeln("Hello from locale 0!");
on Locales[2] do begin writeln("Hello from locale 1!");
writeln("Goodbye from locale 0!");
```

Data-Driven On-Clauses

- **In practice, on-clauses typically refer to variables rather than specific locales:**

```
begin on A[i,j] do
        bigComputation(A);

begin on node.left do
        search(node.left);
```

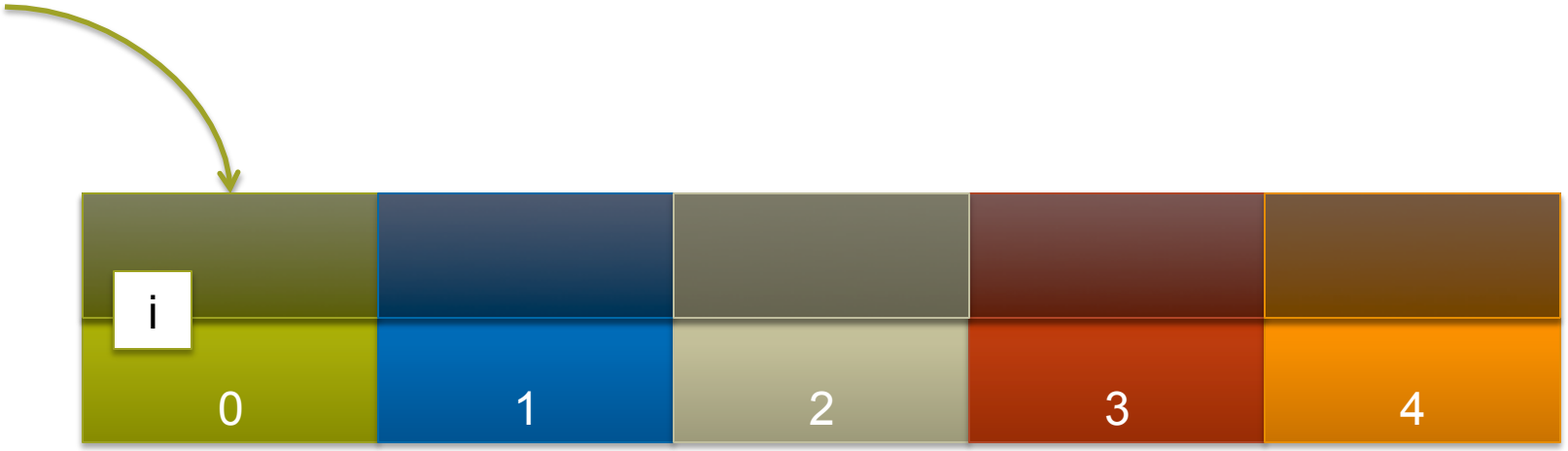
Q: How does data get mapped to locales to begin with?

A (high-level): distributions (see “data parallelism” section)

A (low-level): on-clauses and lexical scoping…

Chapel: Scoping and Locality

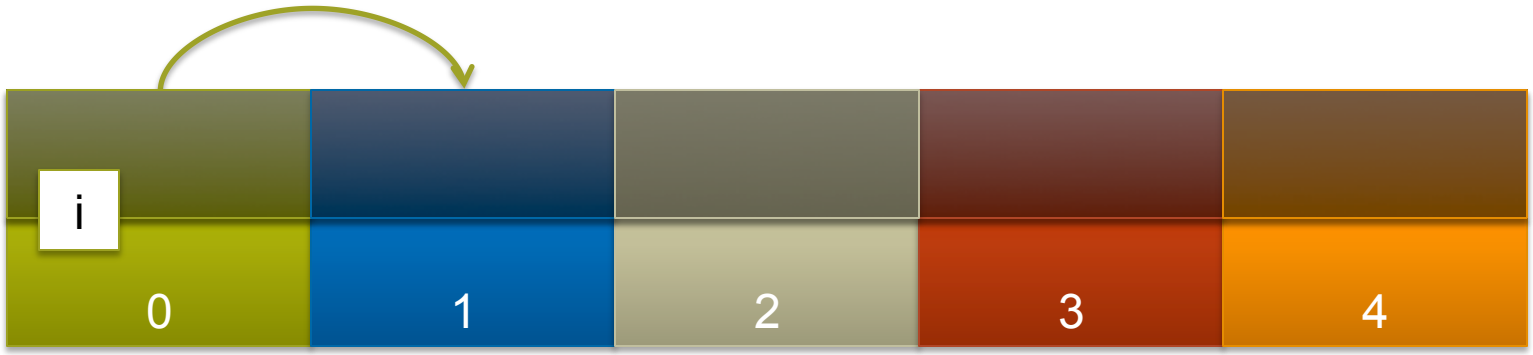
```
var i: int;
```



Locales (think: "compute nodes")

Chapel: Scoping and Locality

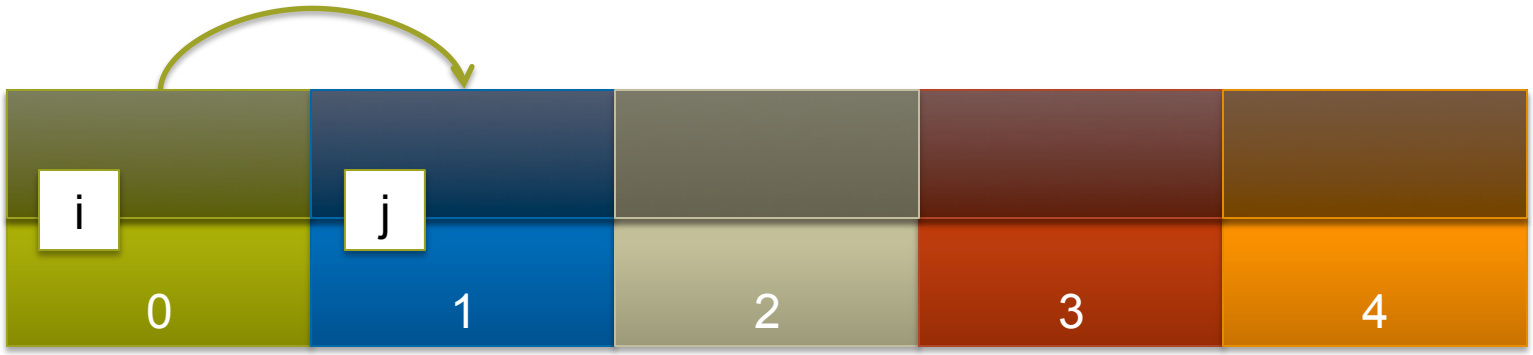
```
var i: int;
on Locales[1] {
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

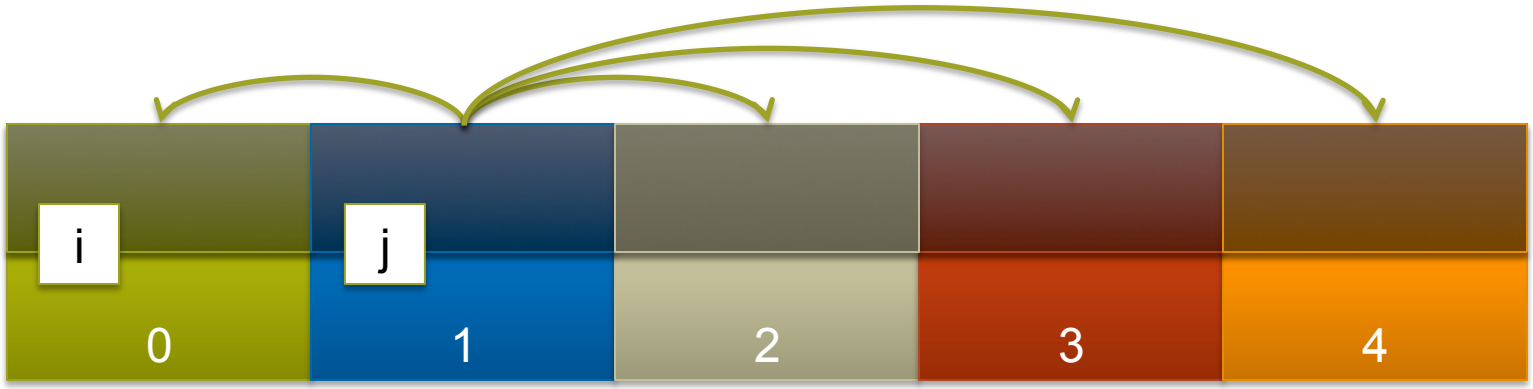
```
var i: int;
on Locales[1] {
  var j: int;
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

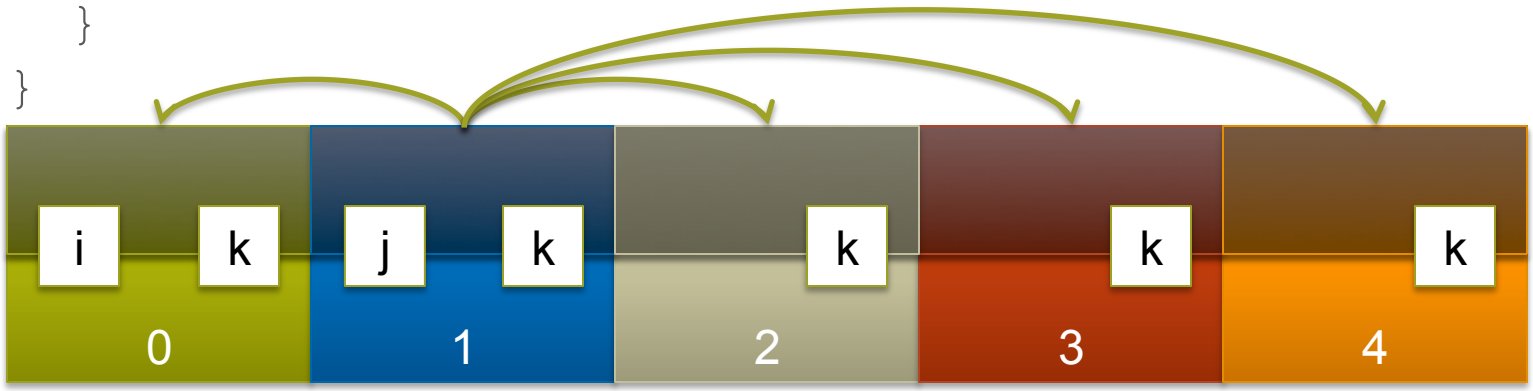
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
```



Locales (think: “compute nodes”)

Chapel: Scoping and Locality

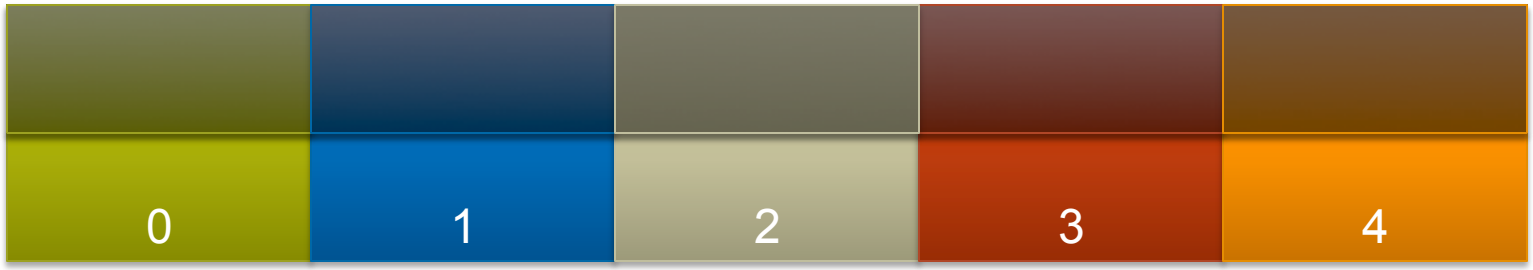
```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      // within this scope, i, j, and k can be referenced;
      // the implementation manages the communication for i and j
      // (Chapel is a PGAS language)
    }
  }
}
```



Locales (think: "compute nodes")

Chapel and PGAS

- **Chapel is PGAS, but unlike most, it's not limited to SPMD**
  - ⇒ never think about "the other copies of the program"
  - ⇒ "global name/address space" comes from lexical scoping
    - as in traditional languages, each declaration creates a variable
    - variables are stored on the locale where the task declaring it is executing



Locales (think: "compute nodes")

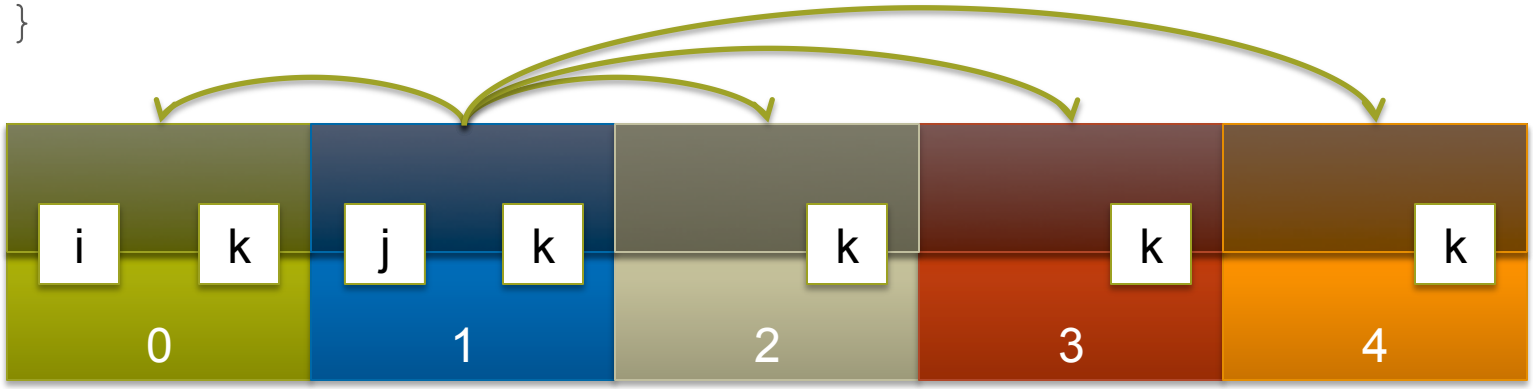
Chapel: Locality Queries

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;

      if (j.locale == here) then …
    }
  }
}
```

Apply '.locale' to any expression to query the locale where it lives

'here' represents the locale where the current task is running



Locales (think: "compute nodes")

Rearranging Locales

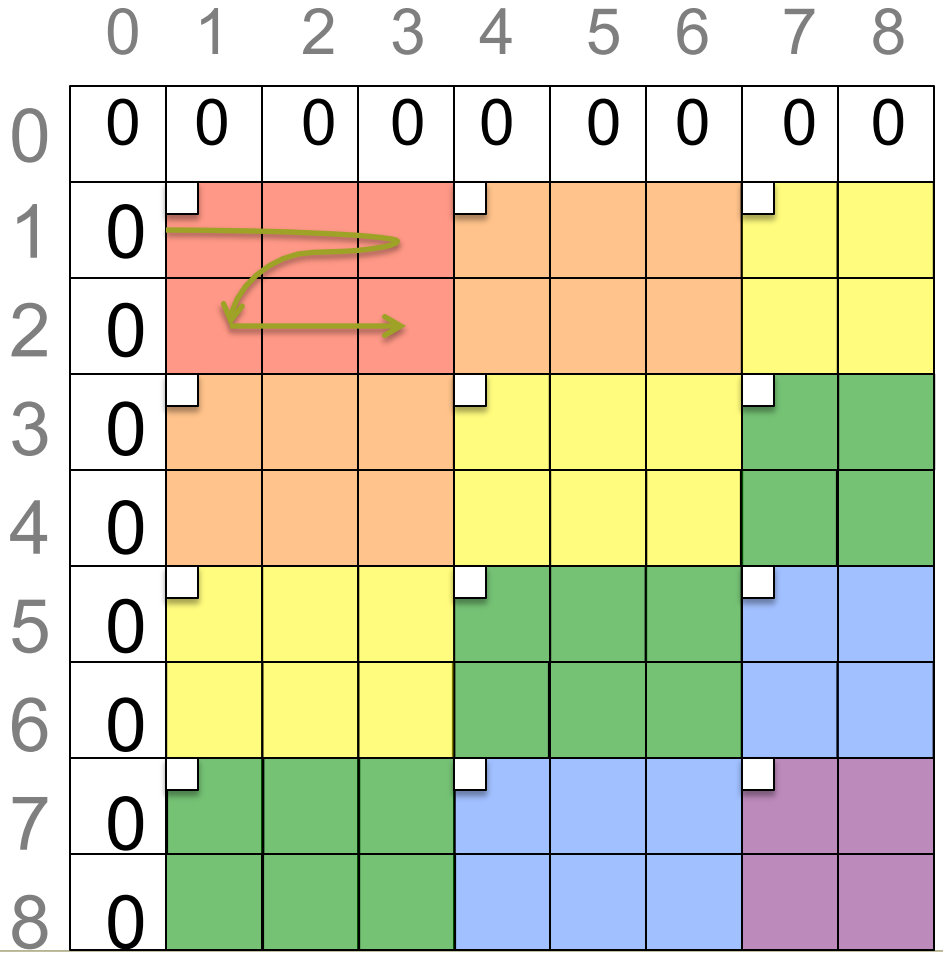
Create locale views with standard array operations:

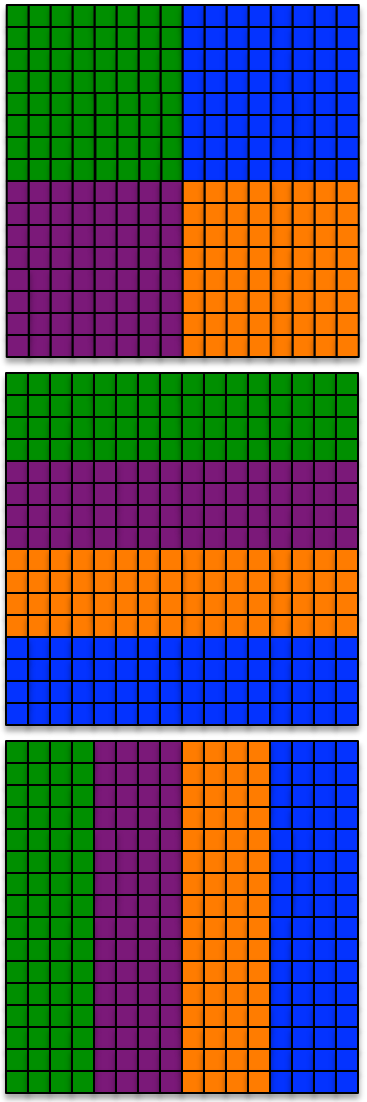
```
var TaskALocs = Locales[0..1];
var TaskBLocs = Locales[2..];

var Grid2D = reshape(Locales, {1..2, 1..4});
```

Distributed Smith-Waterman

Now, what about distributed memory?





Distributed Smith-Waterman

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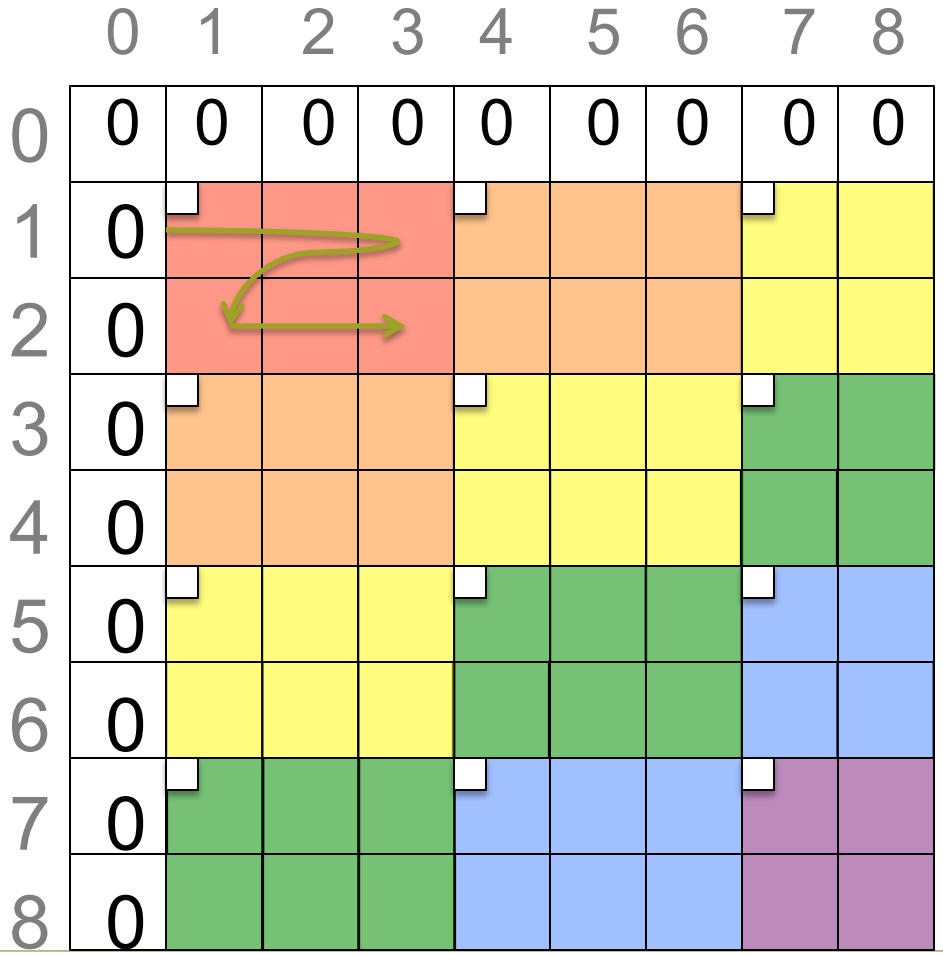

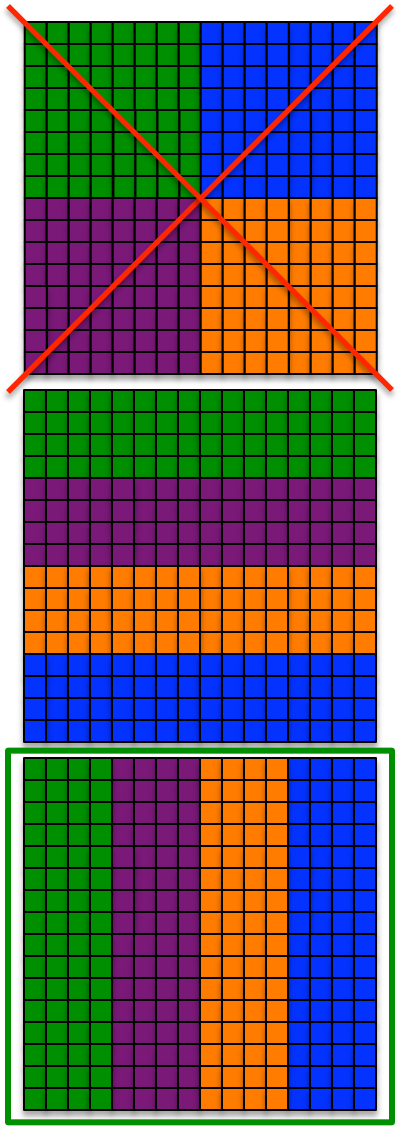

Distributed Smith-Waterman

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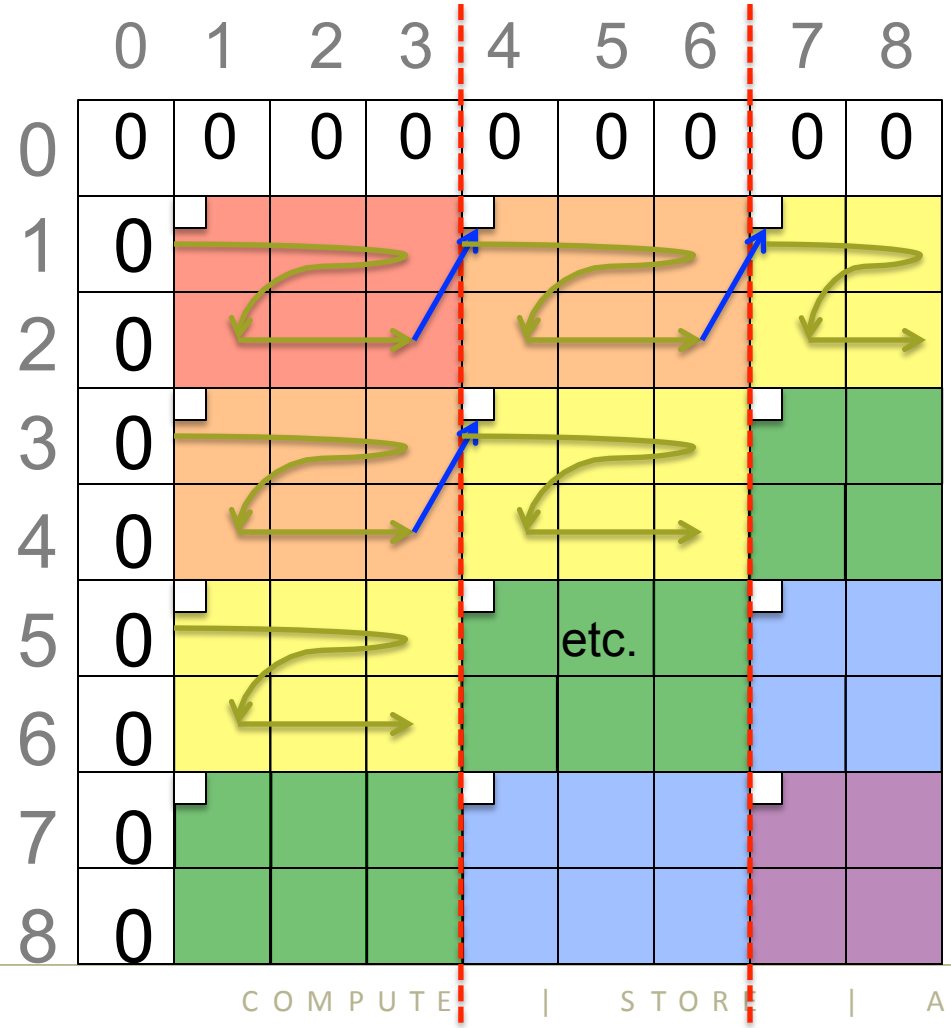
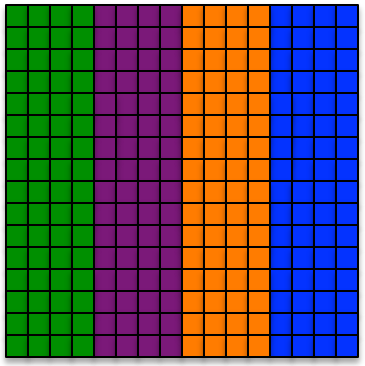


Advantages:

- Good cache behavior: Nice fat blocks of data touchable in memory order
- Pipeline parallelism: Good utilization once pipeline is filled



Distributed Smith-Waterman

Distributed Chunked Data-Driven Task-Parallel Approach:

```
const Hspace = {0..n, 0..n};
const LocaleGrid = Locales.reshape({0..#numLocales, 0..0});
const DistHSpace = Hspace dmapped Block(Hspace, LocaleGrid);
var H: [DistHSpace] int;

proc computeH(H: [] int) {
  const ProbSpace = H.domain.translate(1,1);
  const StrProbSpace = ProbSpace by (rowsPerChunk, colsPerChunk);
  var NeighborsDone: [StrProbSpace] atomic int;
…
  proc computeHHelp(x,y) {
    on H[x,y] {
      for (i,j) in ProbSpace[x..#rowsPerChunk, y..#colsPerChunk] do
        H[i,j] = f(H[i-1,j-1], H[i-1,j], H[i,j-1]);
    const eastReady =  NeighborsDone[x,                y+colsPerChunk].fetchAdd(1);
    …etc…
    if (eastReady == 2)  then begin computeHHelp(x,                y+colsPerChunk);
    …etc…
} } }
```

Reshape the 1D Locales array into a 2D column

Block-distribute the data space across the column of locales

Compute each chunk on the locale that owns its initial element

Summary: Primary Locality Concepts

Locales: our abstraction for distributed system resources

On-clauses: a fine-grained way to move data/tasks to locales

Distributions/Domain Maps: a global-view way to distribute computation and data to locales

More Multiresolution Concepts

Chapel's Three Core Multiresolution Concepts

- ☑ **domain maps:** Permit users to specify how domains and arrays are mapped to machine resources
- ☐ **leader-follower iterators:** Permit users to specify the parallelism and work decomposition used by forall loops
  - including zippered forall loops
- ☐ **locale models:** Permit users to model the target architecture and how Chapel should be implemented on it
  - e.g., how to manage memory, create tasks, communicate, …

Motivation for Leader-Follower Iterators

Q: How are parallel loops implemented?

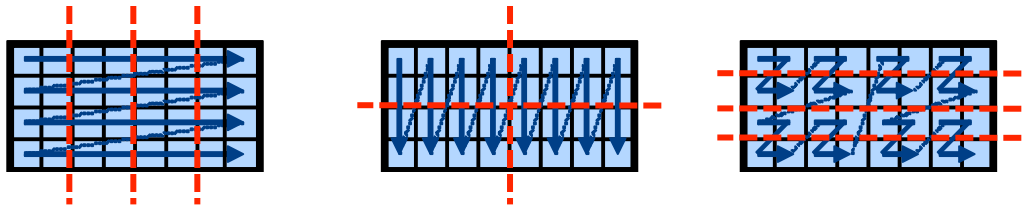
(how many tasks? executing where? how are iterations divided up?)

```
forall k in Elems { … }
```

Q2: What about zippered data parallel operations?

(how to reconcile potentially conflicting parallel implementations?)

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



A *B* *C*

A: Via Leader-Follower Iterators…

Leader-Follower Iterators: Definition

- **Chapel defines forall loops using *leader-follower iterators*:**
  - *leader iterators:* create parallelism, assign iterations to tasks
  - *follower iterators:* serially execute work generated by leader

- **Given…**

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

…*A* is defined to be the *leader*

…*A*, *B*, and *C* are all defined to be *followers*

- **Domain maps support default leader-follower iterators**
  - specify parallel traversal of a domain's indices/array's elements
  - typically written to leverage affinity

Leader-Follower Iterators: Rewriting

***Conceptually*, the Chapel compiler translates:**

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

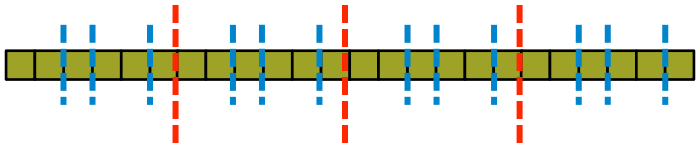
into:

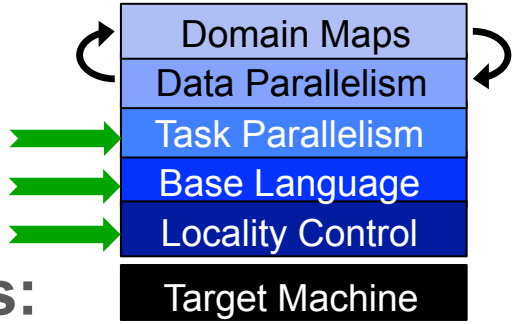
```
inlined A.lead() iterator, which creates tasks that yield work {
  for (a,b,c) in zip(A.follow(work),
                     B.follow(work)
                     C.follow(work)) do
    a = b + alpha * c;
}
```

Writing Leaders and Followers (notionally)

Leader iterators are defined using task/locality features:

```
iter BlockArr.lead() {
  coforall loc in Locales do
    on loc do
      coforall tid in 0..#here.maxTaskPar do
        yield computeMyChunk(loc.id, tid);
}
```





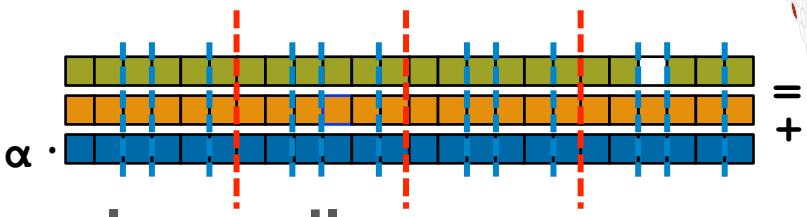
Follower iterators simply use serial features:

```
iter BlockArr.follow(work) {
  for i in work do
    yield accessElement(i);
}
```

Leader-Follower Iterators: Rewriting (notionally)

- Putting it all together, the following loop…

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



…would get rewritten by the Chapel compiler as:

```
coforall loc in Locales do
  on loc do
    coforall tid in 0..#here.maxTaskPar {
      const work = computeMyChunk(loc.id, tid);
      for (a,b,c) in zip(A.follow(work),
                         B.follow(work)
                         C.follow(work)) do
        a = b + alpha * c;
    }
```

Leader-Follower Summary

- **Most languages define a fixed menu of parallel loop styles**
  - where “no parallel loops” is a common choice
- **Leader-follower iterators…**

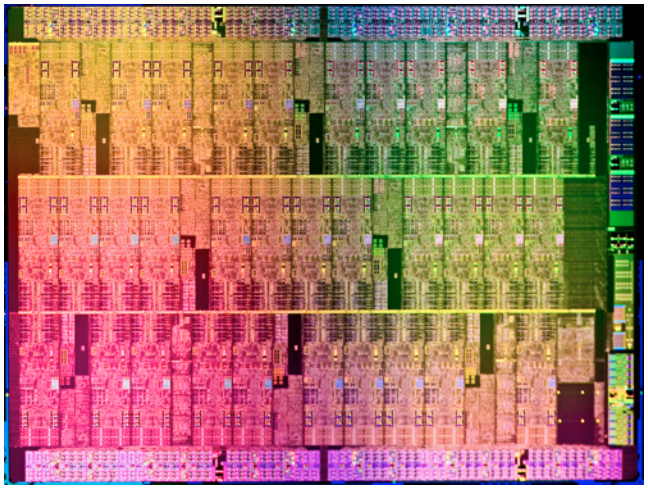
  …move such policies into user-space

  …expose them to the end-user through data parallel abstractions

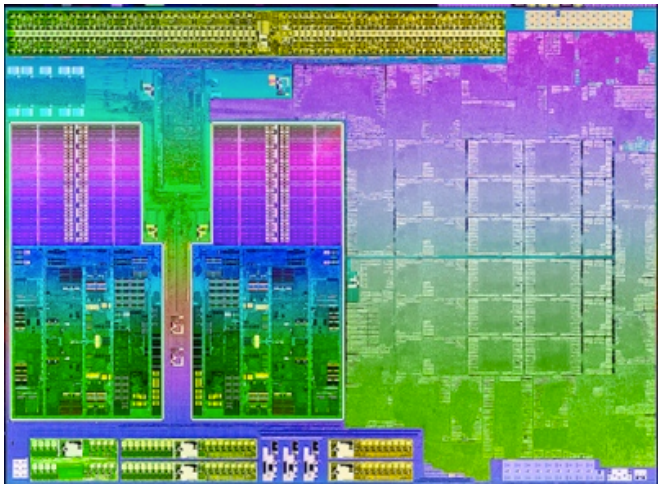
Chapel's Three Core Multiresolution Concepts

- ☑ **domain maps:** Permit users to specify how domains and arrays are mapped to machine resources
- ☑ **leader-follower iterators:** Permit users to specify the parallelism and work decomposition used by forall loops
  - including zippered forall loops
- ☐ **locale models:** Permit users to model the target architecture and how Chapel should be implemented on it
  - e.g., how to manage memory, create tasks, communicate, …

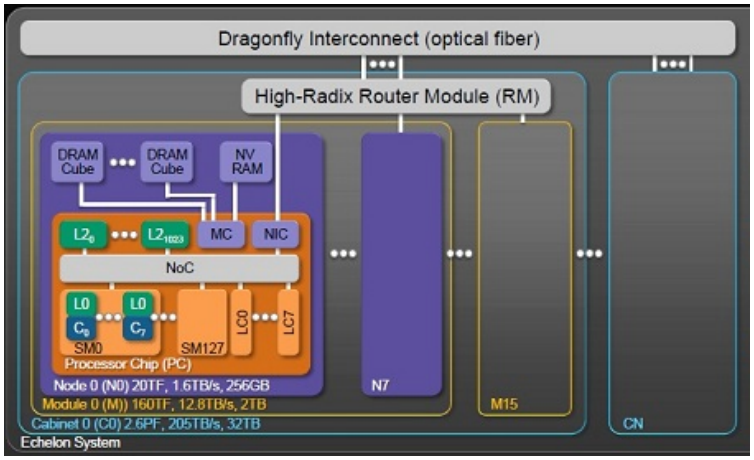
Prototypical Next-Gen Processor Technologies



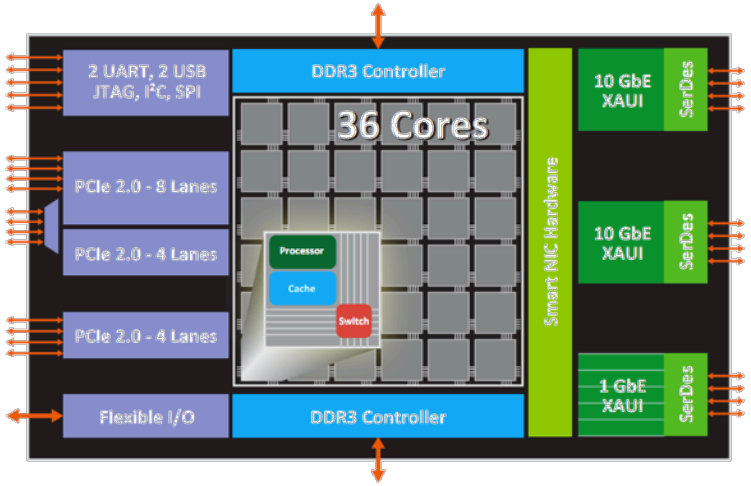
Intel MIC



AMD APU



Nvidia Echelon



Tilera Tile-Gx

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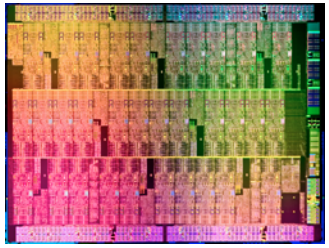
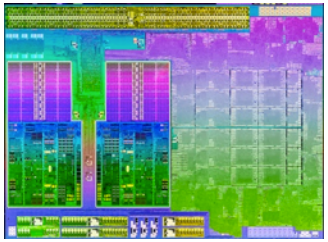
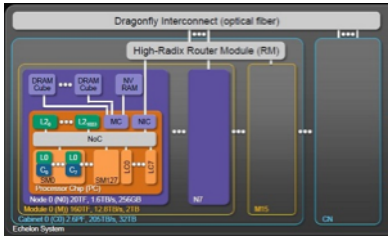
http://insidehpc.com/2010/11/26/nvidia-reveals-details-of-echelon-gpu-designs-for-exascale/ http://tilera.com/sites/default/files/productbriefs/Tile-Gx%203036%20SB012-01.pdf

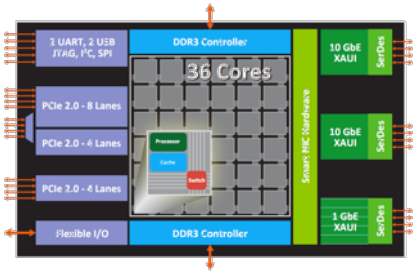
COMPUTE | STORE | ANALYZE

General Characteristics of These Architectures









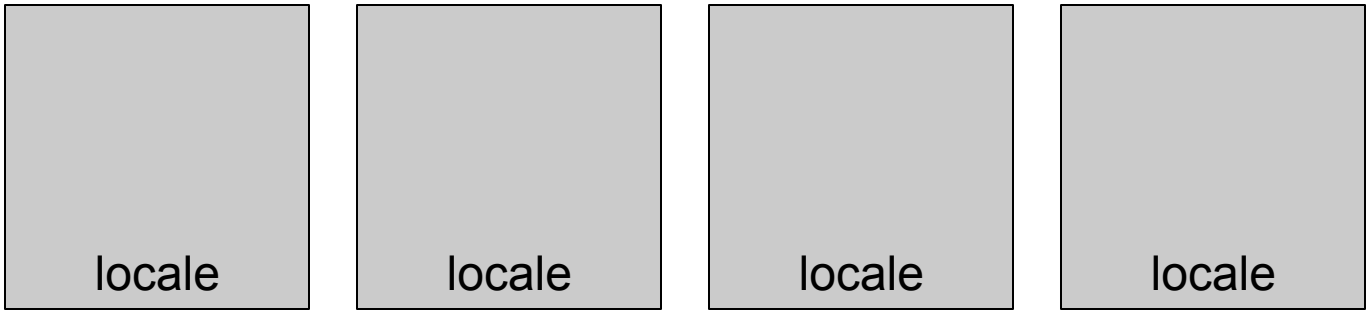
- **Increased hierarchy and/or sensitivity to locality**
- **Potentially heterogeneous processor/memory types**

⇒ Next-gen programmers will have a lot more to think about at the node level than in the past

Locales, Traditionally

Concept:

- Traditionally, Chapel has supported a 1D array of locales
  - users can reshape/slice to suit their computation's needs



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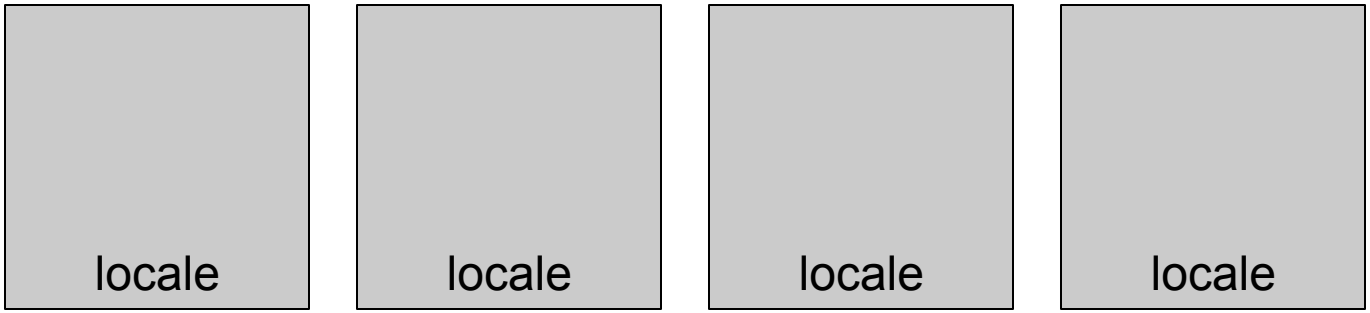
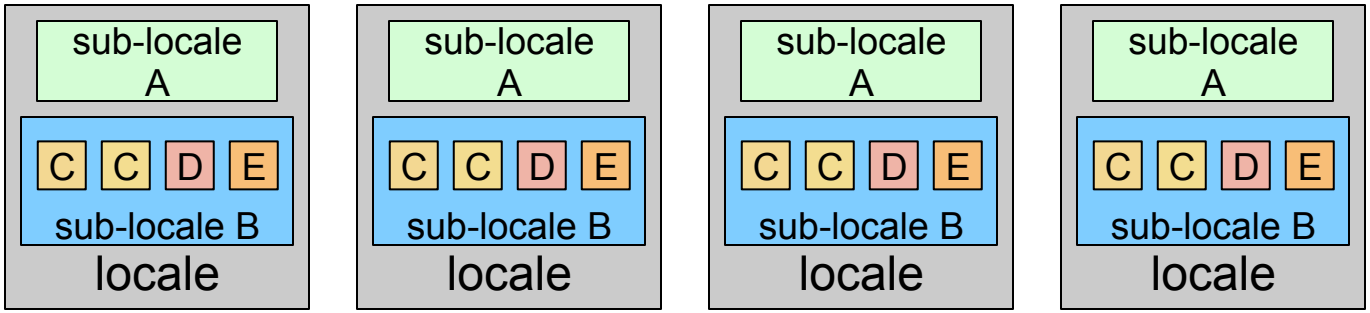


- Apart from queries, no further visibility into locales
  - no mechanism to refer to specific NUMA domains, processors, memories, …
  - assumption: compiler, runtime, OS, HW can handle intra-locale concerns
- Supports horizontal (inter-node) locality well
  - but not vertical (intra-node)

Hierarchical Locales

Concept:

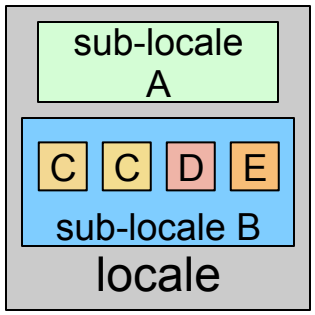
- Support locales within locales to describe architectural sub-structures within a node



- As with traditional locales, *on-clauses* and *domain maps* are used to map tasks and variables to sub-locales
- Locale structure is defined using Chapel code
  - permits architectural descriptions to be specified in-language
  - continues the multiresolution philosophy
  - introduces a new Chapel role: *architectural modeler*

Defining Hierarchical Locales

1) Define the processor's abstract block structure



2) Define how to run a task on any sublocale

3) Define how to allocate/access memory on any sublocale

For more information, come visit our Emerging Tech exhibit on this topic, this week on the show floor: booth #233!

Hierarchical Locale Summary

- **Most programming models assume a certain type of target architecture**
  - this is why MPI/OpenMP/UPC/CUDA/… have restricted applicability
- **Hierarchical Locales**

  …move the definition of new architectural models to user space

  …are exposed to the end-user via Chapel's traditional locality features

Multiresolution Summary

Chapel's multiresolution philosophy allows users to write…

- …**custom array implementations** via domain maps
- …**custom parallel iterators** via leader-follower iterators
- …**custom architectural models** via hierarchical locales

The result is a language that moves crucial policies for managing data locality out of the language's definition and into an expert user's hand…

…while making them available to end-users through high-level abstractions

For More Information on…

…domain maps

User-Defined Distributions and Layouts in Chapel: Philosophy and Framework [slides], Chamberlain, Deitz, Iten, Choi; HotPar'10, June 2010.

Authoring User-Defined Domain Maps in Chapel [slides], Chamberlain, Choi, Deitz, Iten, Litvinov; Cug 2011, May 2011.

…leader-follower iterators

User-Defined Parallel Zippered Iterators in Chapel [slides], Chamberlain, Choi, Deitz, Navarro; PGAS 2011, October 2011.

…hierarchical locales

Hierarchical Locales: Exposing Node-Level Locality in Chapel, Choi; 2nd KIISE-KOCSEA SIG HPC Workshop talk, November 2013.

Status: all of these concepts are in use in every Chapel program today
(pointers to code/docs in the release available on request)

Summary

Higher-level programming models can help insulate algorithms from parallel implementation details

- yet, without necessarily abdicating control
- Chapel does this via its multiresolution design
  - these avoid locking crucial policy decisions into the language

The result cleanly separates the roles of domain scientist, parallel programmer, and compiler/runtime

Questions about Locality in Chapel?

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