Locality By Example
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Locality Features

Domain Maps
Data Parallelism
Task Parallelism
Base Language
Locality Control
Target Machine
Lower-level Chapel
"Hello World" in Chapel: a Multi-Locale Version

● Multi-locale Hello World

```chapel
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)
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:

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

```chapel
cconst nodeMemory = here.physicalMemory();
cconst systemMemory = + reduce Locales.physicalMemory();
cconst maxNodeMemory = max reduce Locales.physicalMemory();
cconst 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:

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

Locales (think: “compute nodes”)
Chapel: Scoping and Locality

```chapel
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

```chapel
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
Chapel: Locality Queries

```chapel
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      if (j.locale == here) then ...
    }
  }
}
```

- **Locales**: (think: “compute nodes”)
- Apply `.locale` to any expression to query the locale where it lives
- `.locale` returns the locale where the current task is running
- `here` represents the locale where the current task is running
Rearranging Locales

Create locale views with standard array operations:

```plaintext
var TaskALocs = Locales[0..1];
var TaskBLocs = Locales[2..];
var Grid2D = reshape(Locales, {1..2, 1..4});
```

```
Locales: L0 L1 L2 L3 L4 L5 L6 L7
TaskALocs: L0 L1
TaskBLocs: L2 L3 L4 L5 L6 L7
Grid2D: L0 L1 L2 L3 L4 L5 L6 L7
```
### Distributed Smith-Waterman

Now, what about distributed memory?

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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

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Distributed Smith-Waterman

**Distributed Chunked Data-Driven Task-Parallel Approach:**

```chapel
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: 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...
  ```chapel
define 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:

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

into:

```chapel
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:

```chapel
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:

```chapel
iter BlockArr.follow(work) {
    for i in work do
        yield accessElement(i);
}
```
Leader-Follower Iterators: Rewriting (notionally)

Putting it all together, the following loop...

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

...would get rewritten by the Chapel compiler as:

```plaintext
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

Sources:
http://download.intel.com/pressroom/images/Aubrey_Isle_die.jpg
http://www.zdnet.com/amds-trinity-processors-take-on-intels-ivy-bridge-3040155225/
http://tilera.com/sites/default/files/productbriefs/Tile-Gx%203036%20SB012-01.pdf
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
Locales, Traditionally

Concept:

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

- 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

![Diagram showing a hierarchical structure with locales and sub-locales]

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
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


*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


**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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