Chapel: Overview and Features for Heterogeneity

Brad Chamberlain, Chapel Team, Cray Inc.

Heterogeneous C++ Working Group

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Plan for this morning

- Chapel context
- Overview of example core Chapel features
- Additional detail on features related to heterogeneity
- Feel free to interrupt for Questions / Discussion

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Chapel and Heterogeneity in a Nutshell

- **Chapel's design supports hardware heterogeneity**
  - and in a way that is user-extensible without compiler changes
- **That said, in practice…**

  …virtually all of our work has been on homogeneous cases

  …we haven't spend much time on many of the hardest cases
    - e.g., no FPGA work, less GPU work than we'd like

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What is Chapel?

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What is Chapel?

Chapel: A productive parallel programming language

- portable
- open-source
- a collaborative effort

Goals:

- Support general parallel programming
  - "any parallel algorithm on any parallel hardware"
- Make parallel programming at scale far more productive

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Scalable Parallel Programming Concerns

Q: What do HPC programmers need from a language?

A: ***Serial Code:*** **Software engineering and performance**

Parallelism: **What should execute simultaneously?**

Locality: **Where should those tasks execute?**

Mapping: **How to map the program to the system?**

Separation of Concerns: **Decouple these issues**

Chapel is a language designed to address these needs from first principles

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Chapel and Other Languages

Chapel strives to be as…

…**programmable** as Python

…**fast** as Fortran

…**scalable** as MPI, SHMEM, or UPC

…**portable** as C

…**flexible** as C++

…**fun** as [your favorite programming language]

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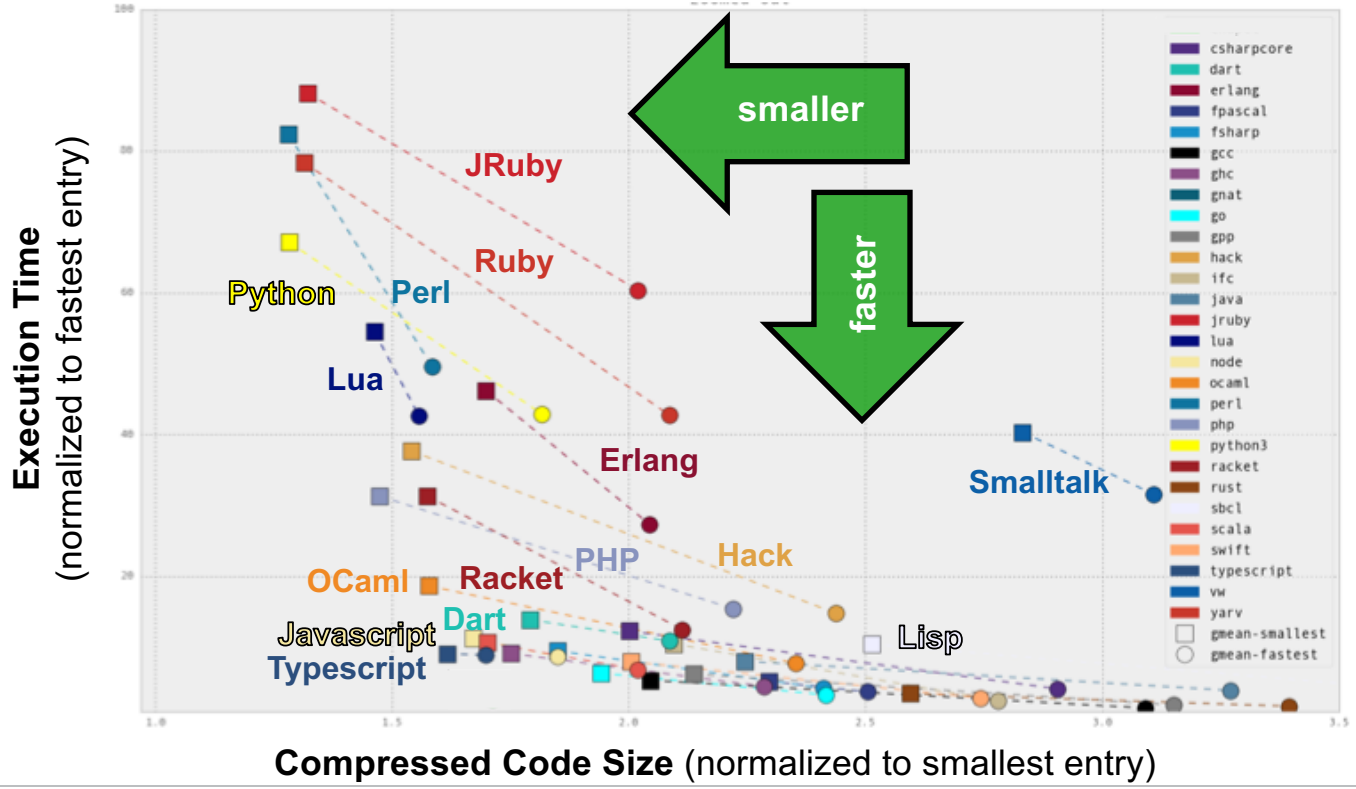
CLBG Cross-Language Summary
(Oct 2017 standings)



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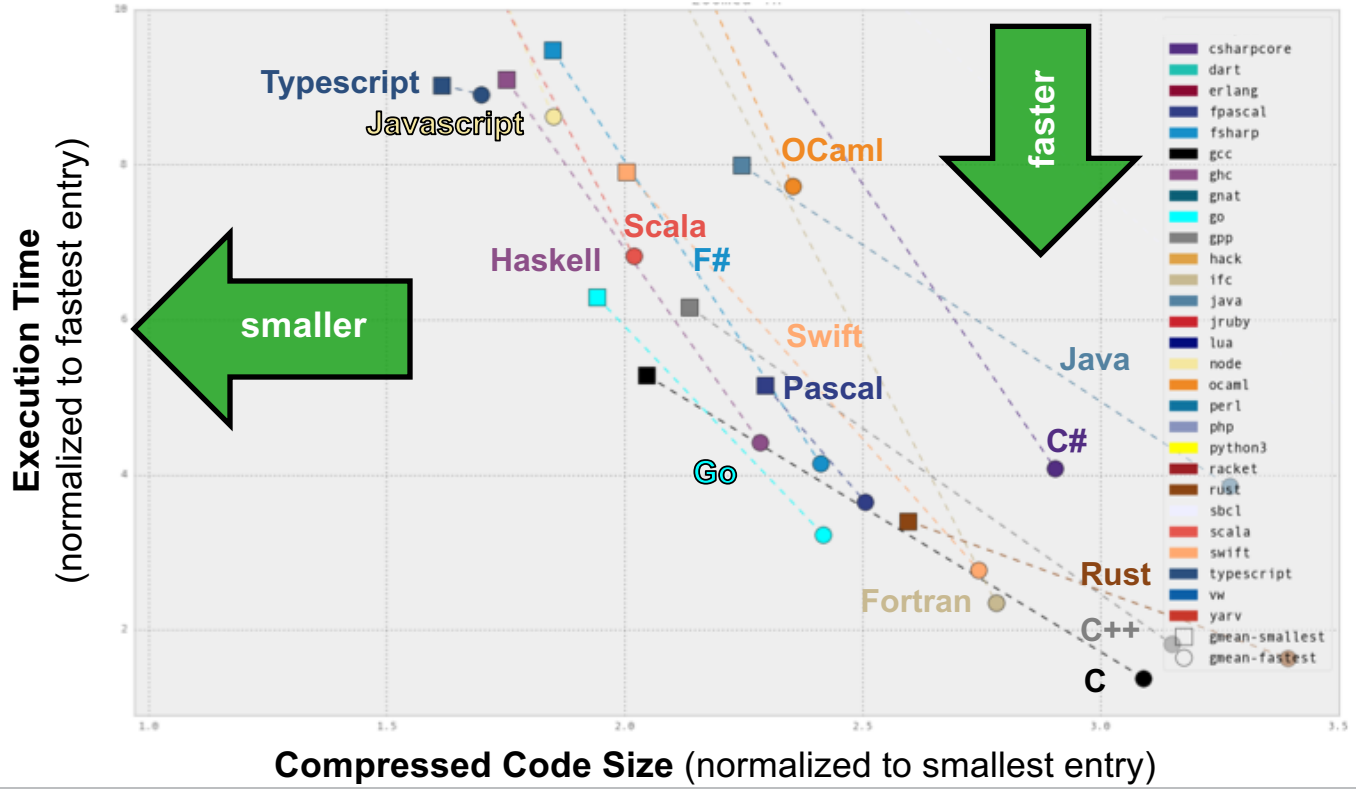
CLBG Cross-Language Summary
(Oct 2017 standings, zoomed in)



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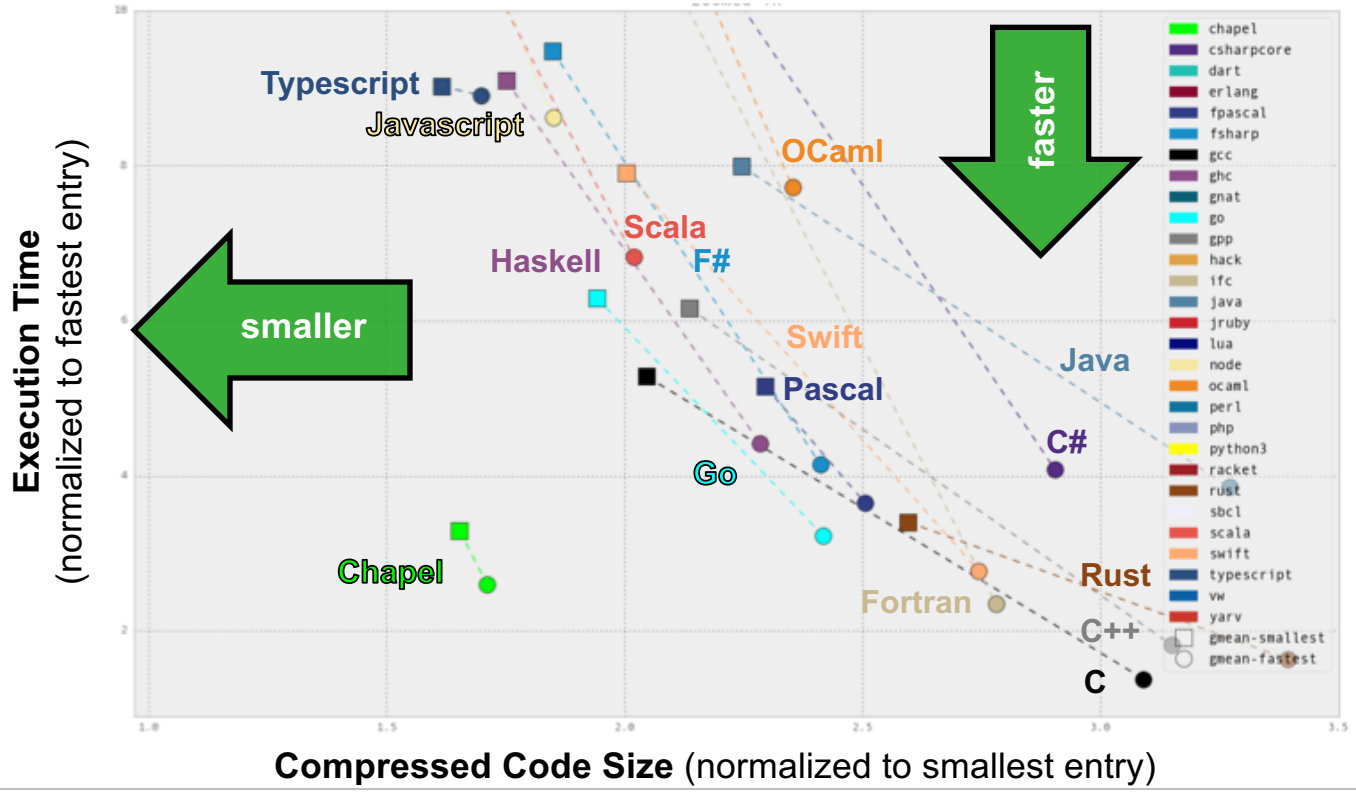

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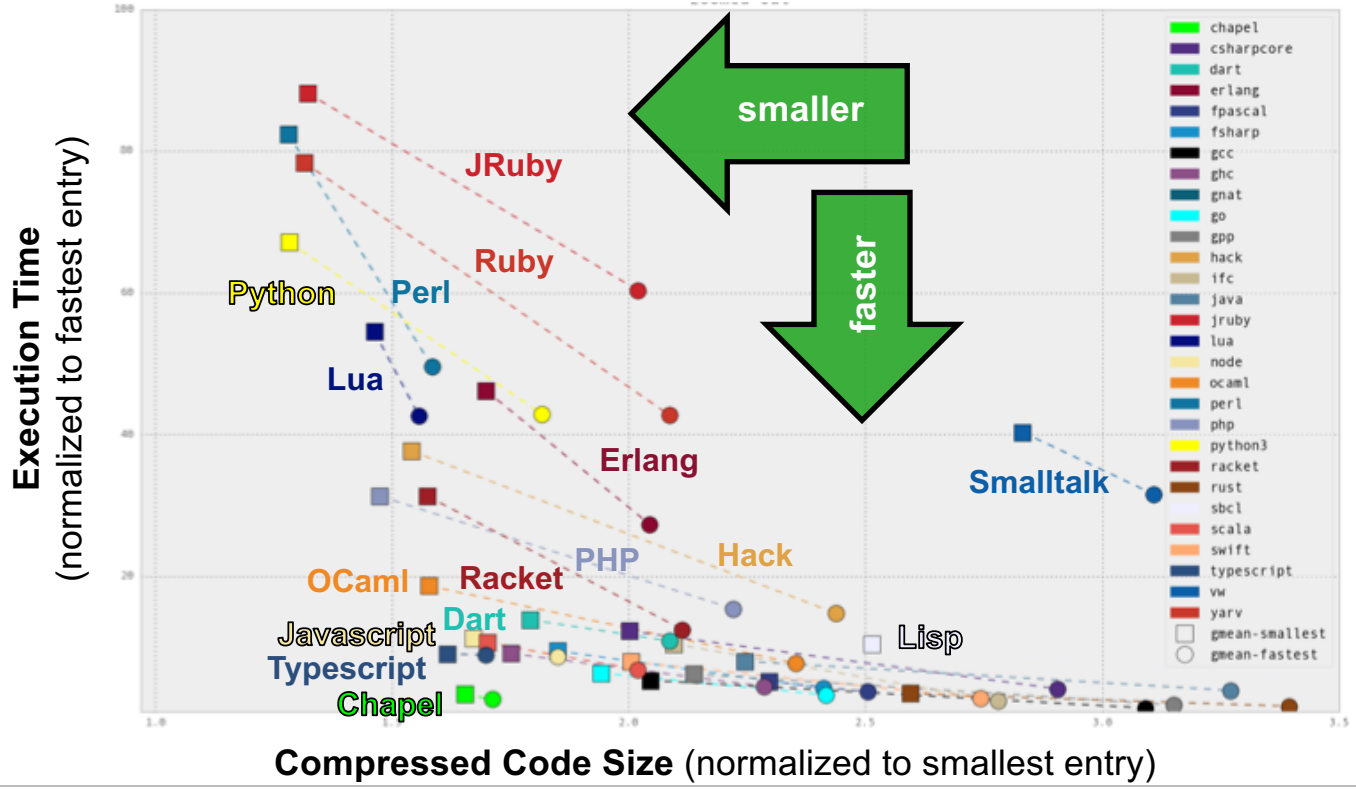

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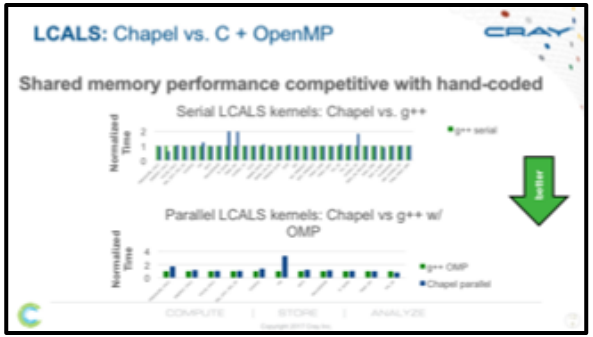
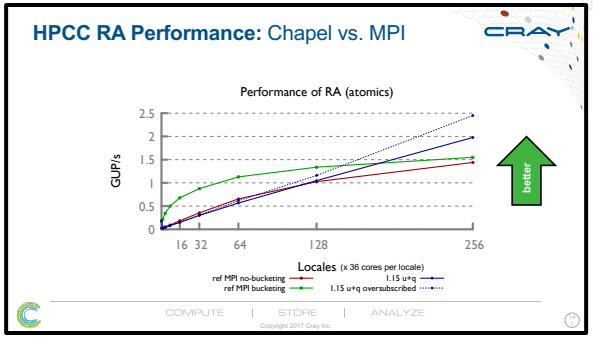
Chapel Performance: HPC Benchmarks



LCALS

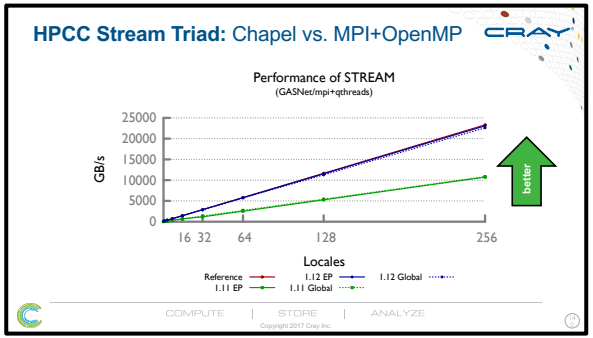
HPCC RA

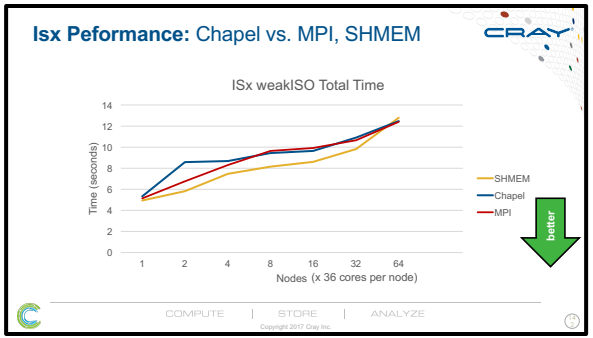


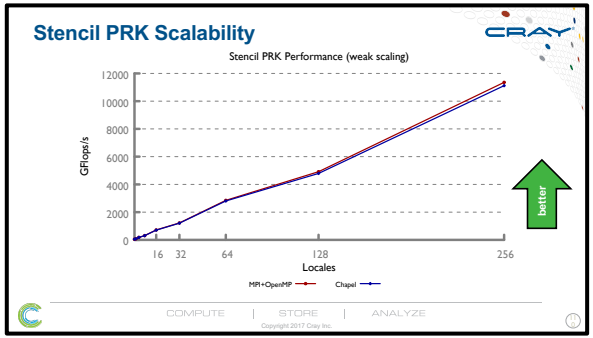
STREAM Triad

ISx

PRK Stencil







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Nightly performance graphs online at: https://chapel-lang.org/perf

The Chapel Team at Cray (May 2017)

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Chapel Community Partners

Lawrence Berkeley
National Laboratory

(and several others…)

https://chapel-lang.org/collaborations.html

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Introduction to Chapel, by Example

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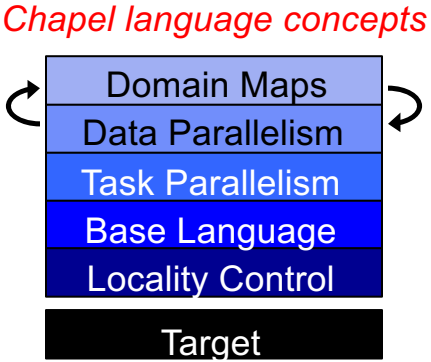
Chapel language feature areas



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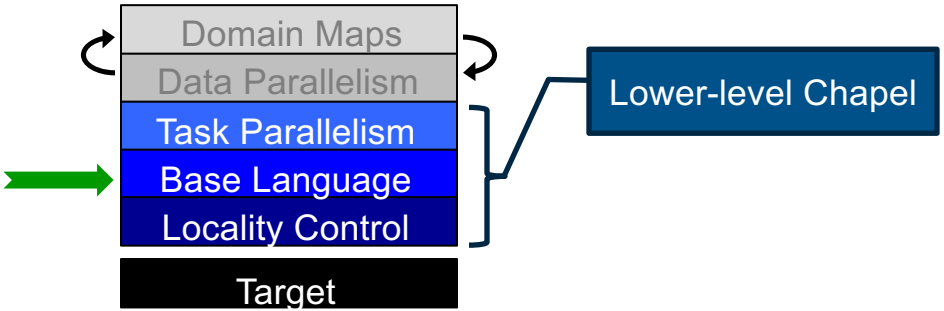
Base Language



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Base Language Features, by example

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
config const n = 10;

for f in fib(n) do
  writeln(f);
```

```
0
1
1
2
3
5
8
...
```


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Base Language Features, by example

Configuration declarations
(to avoid command-line argument parsing)
`./a.out --n=1000000`

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
config const n = 10;

for f in fib(n) do
  writeln(f);
```

```
0
1
1
2
3
5
8
...
```


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Base Language Features, by example

Modern iterators

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
config const n = 10;

for f in fib(n) do
  writeln(f);
```

```
0
1
1
2
3
5
8
...
```


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Base Language Features, by example

Static type inference for:
- arguments
- return types
- variables

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
config const n = 10;

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```

```
0
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...
```


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Base Language Features, by example

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

Zippered iteration

```
config const n = 10;

for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
…
```


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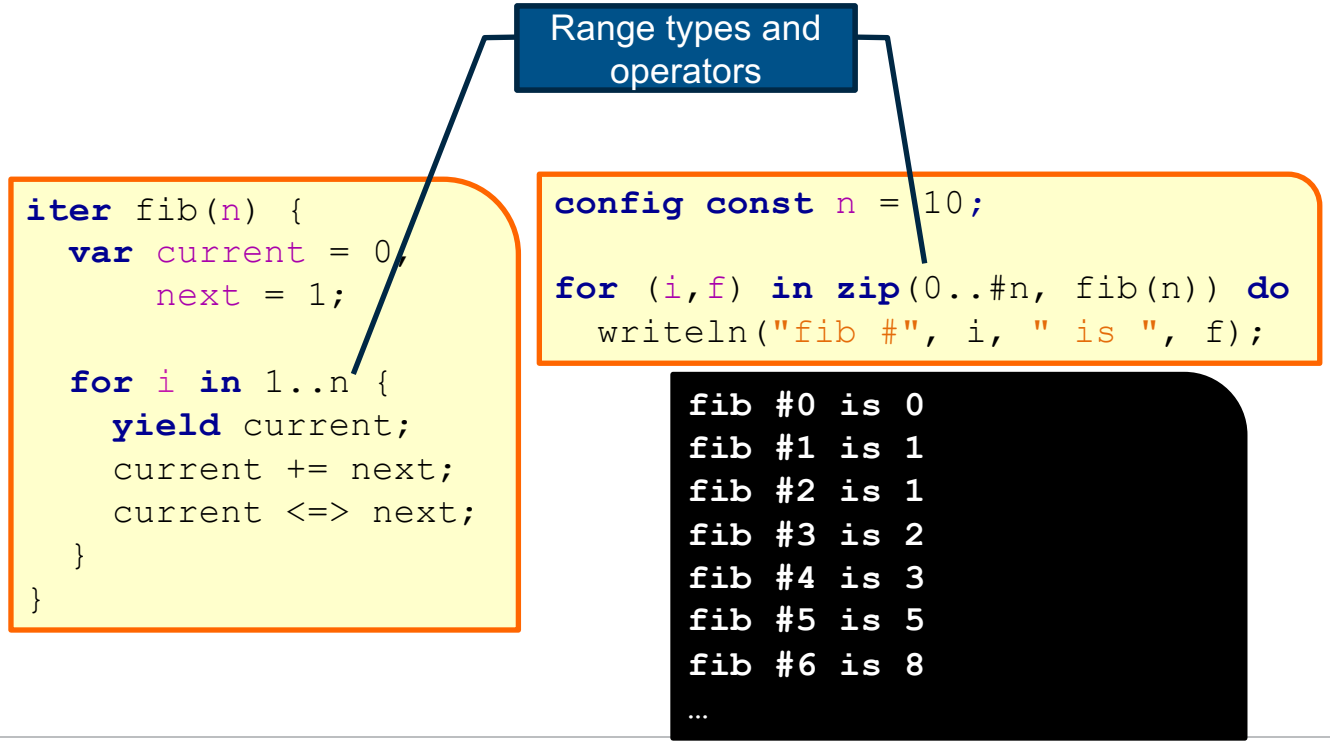
Base Language Features, by example



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Base Language Features, by example

```
iter fib(n) {
  var current = 0,
      next = 1;

  for i in 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

tuples

```
config const n = 10;

for (i,f) in zip(0..#n, fib(n)) do
  writeln("fib #", i, " is ", f);
```

```
fib #0 is 0
fib #1 is 1
fib #2 is 1
fib #3 is 2
fib #4 is 3
fib #5 is 5
fib #6 is 8
…
```


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Base Language Features, by example

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```


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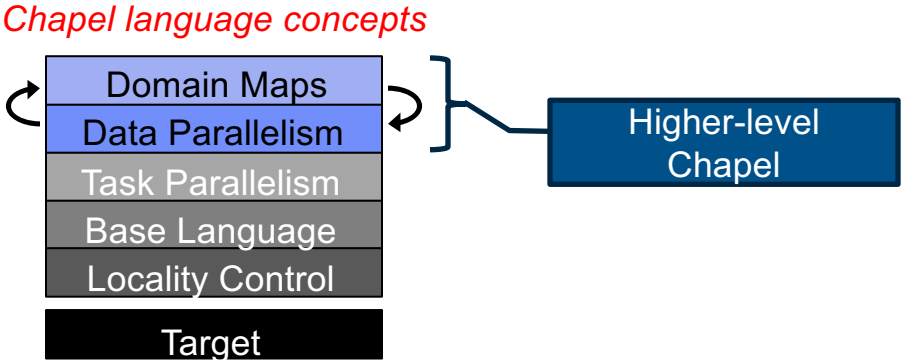
Data Parallelism in Chapel



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Data Parallelism, by example

dataParallel.chpl

```
config const n = 1000;
var D = {1..n, 1..n};

var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Data Parallelism, by example

Domains (Index Sets)

dataParallel.chpl

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config const n = 1000;
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4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Data Parallelism, by example

Arrays

dataParallel.chpl

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4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Data Parallelism, by example

Data-Parallel Forall Loops

dataParallel.chpl

```
config const n = 1000;
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var A: [D] real;
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4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Data Parallelism, by example

This is a shared memory program

Nothing has referred to remote locales, explicitly or implicitly

dataParallel.chpl

```
config const n = 1000;
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3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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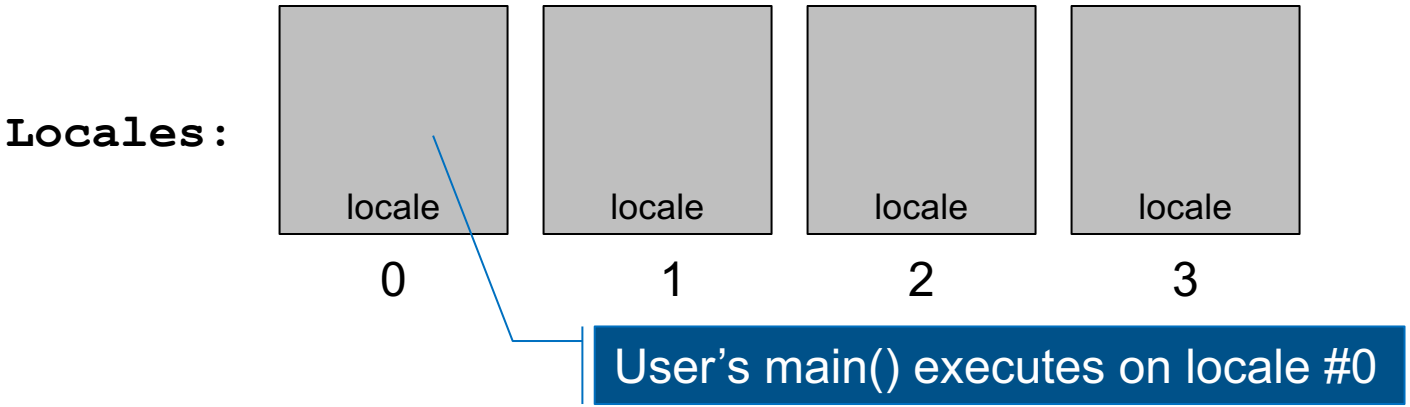
Locales

- Unit of the target system useful for reasoning about locality
  - Each locale can run tasks and store variables
    - Has processors and memory (or can defer to something that does)
  - For most HPC systems, locale == compute node



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Data Parallelism, by example

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dataParallel.chpl

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4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Distributed Data Parallelism, by example

Domain Maps
(Map Data Parallelism to the System)

dataParallel.chpl

```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
2.1 2.3 2.5 2.7 2.9
3.1 3.3 3.5 3.7 3.9
4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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Distributed Data Parallelism, by example

dataParallel.chpl

```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
        dmapped Cyclic(startIdx = (1,1));
var A: [D] real;
forall (i,j) in D do
  A[i,j] = i + (j - 0.5)/n;
writeln(A);
```

Not in the slightest…

- Lowering of code is well-defined
- User can control details
- Part of Chapel's *multiresolution philosophy*…

```
prompt> chpl dataParallel.chpl -o dataParallel
prompt> ./dataParallel --n=5 --numLocales=4
1.1 1.3 1.5 1.7 1.9
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4.1 4.3 4.5 4.7 4.9
5.1 5.3 5.5 5.7 5.9
```


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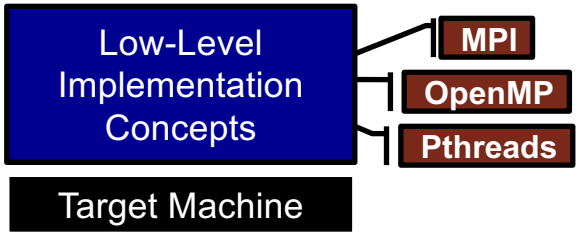
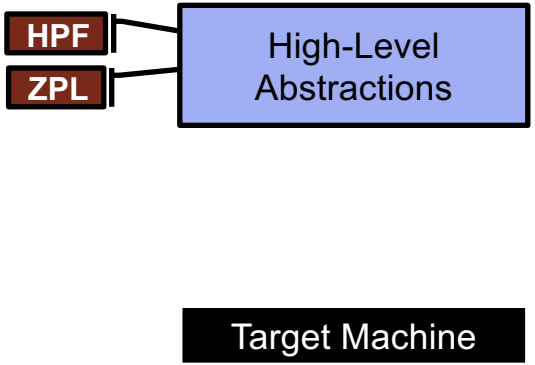
Chapel's Multiresolution Design: Motivation





"Why is everything so tedious/difficult?"

"Why don't my programs trivially port to new systems?"

"Why don't I have more control?"

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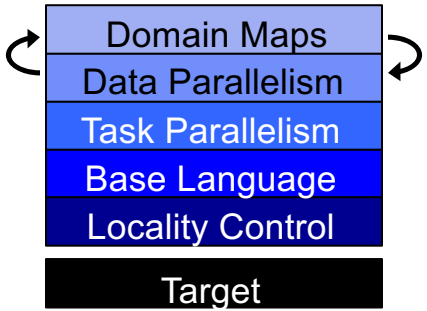
Chapel's Multiresolution Philosophy

Multiresolution Design: **Support multiple tiers of features**

- higher levels for programmability, productivity
- lower levels for greater degrees of control



- build the higher-level concepts in terms of the lower
- permit users to intermix layers arbitrarily

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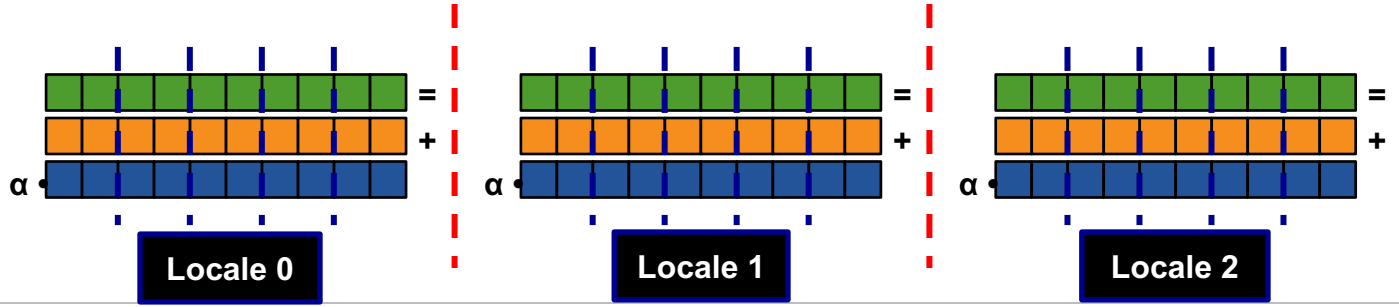
Domain Maps: A Multiresolution Feature

Domain maps are “recipes” that instruct the compiler how to map the global view of a computation…


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

…to the target locales’ memory and processors:



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Authoring Domain Maps

- **Users can write their own domain maps**
  - Implemented within Chapel itself
  - Create an object type per concept:
    - The domain map itself
    - A domain
    - An array
  - Make them satisfy a standard interface
    - e.g., arrays must support iteration, random access, etc.
  - Compiler targets this interface in implementing the language
  - Goal: make the language flexible, future-proof

Note: *all* Chapel arrays are implemented this way

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Distributed Data Parallelism, by example

dataParallel.chpl

```
use CyclicDist;
config const n = 1000;
var D = {1..n, 1..n}
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```

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```


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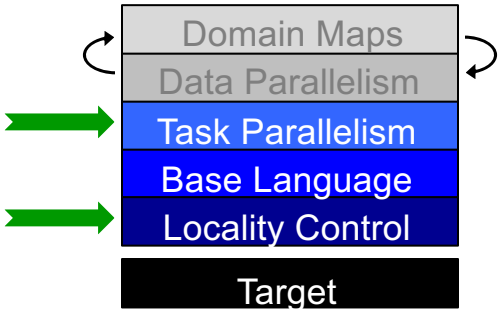
Task Parallelism and Locality Control



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Task Parallelism and Locality, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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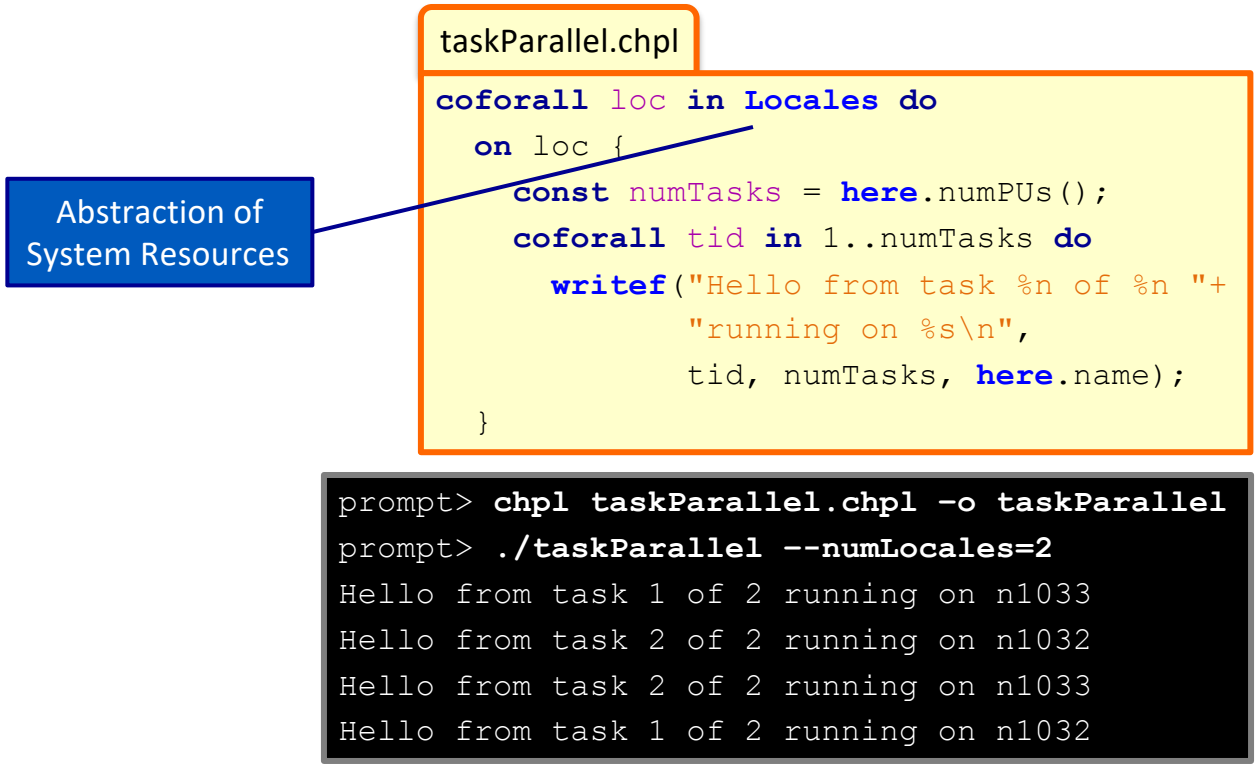
Task Parallelism and Locality, by example



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Task Parallelism and Locality, by example

High-Level Task Parallelism

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
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    coforall tid in 1..numTasks do
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             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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Task Parallelism and Locality, by example

taskParallel.chpl

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    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

Control of Locality/Affinity

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
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Hello from task 1 of 2 running on n1032
```


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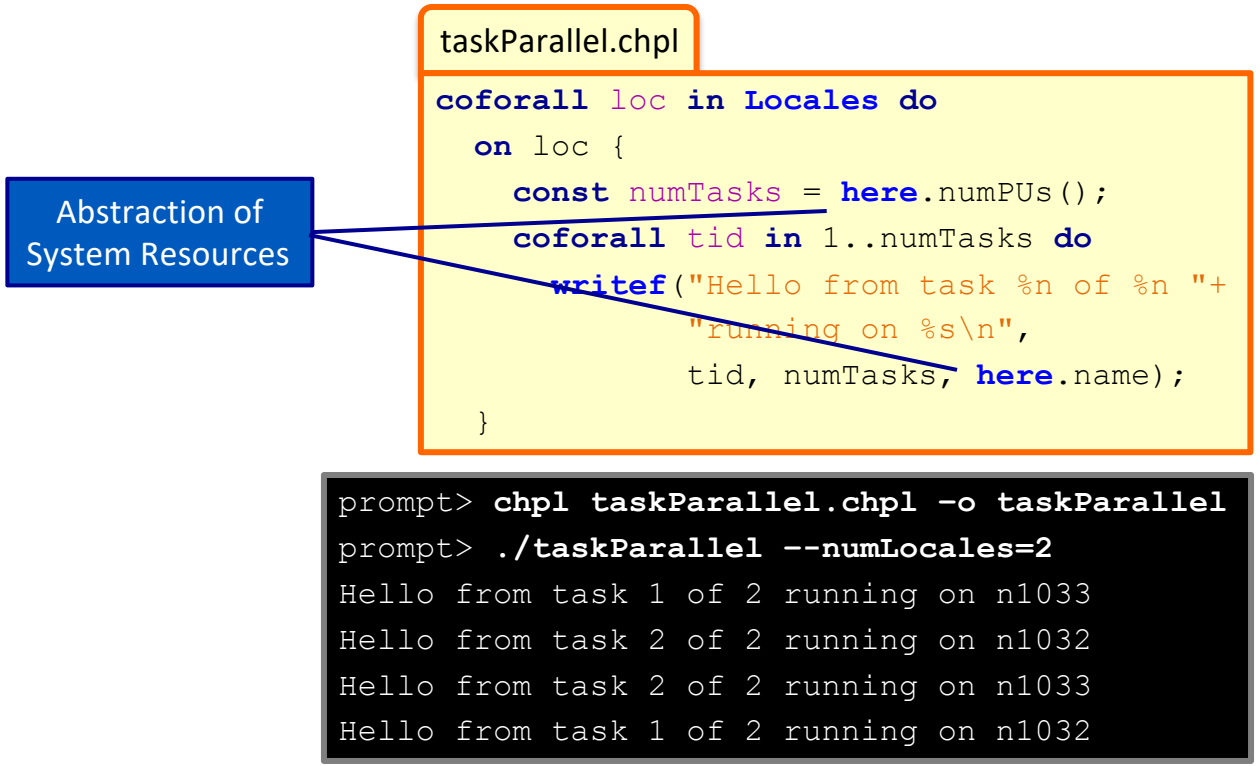
Task Parallelism and Locality, by example



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Task Parallelism and Locality, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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Task Parallelism and Locality, by example

taskParallel.chpl

```
coforall loc in Locales do
  on loc {
    const numTasks = here.numPUs();
    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

Not seen here:

Data-centric task coordination via atomic and full/empty vars

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```

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Task Parallelism and Locality, by example

taskParallel.chpl

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coforall loc in Locales do
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    coforall tid in 1..numTasks do
      writef("Hello from task %n of %n "+
             "running on %s\n",
             tid, numTasks, here.name);
  }
```

```
prompt> chpl taskParallel.chpl -o taskParallel
prompt> ./taskParallel --numLocales=2
Hello from task 1 of 2 running on n1033
Hello from task 2 of 2 running on n1032
Hello from task 2 of 2 running on n1033
Hello from task 1 of 2 running on n1032
```


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Parallelism and Locality: Distinct in Chapel

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

```
coforall i in 1..msgs do
  writeln("Hello from task ", i);
```

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

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

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

```
coforall i in 1..msgs do
  on Locales[i%numLocales] do
    writeln("Hello from task ", i,
            " running on locale ", here.id);
```


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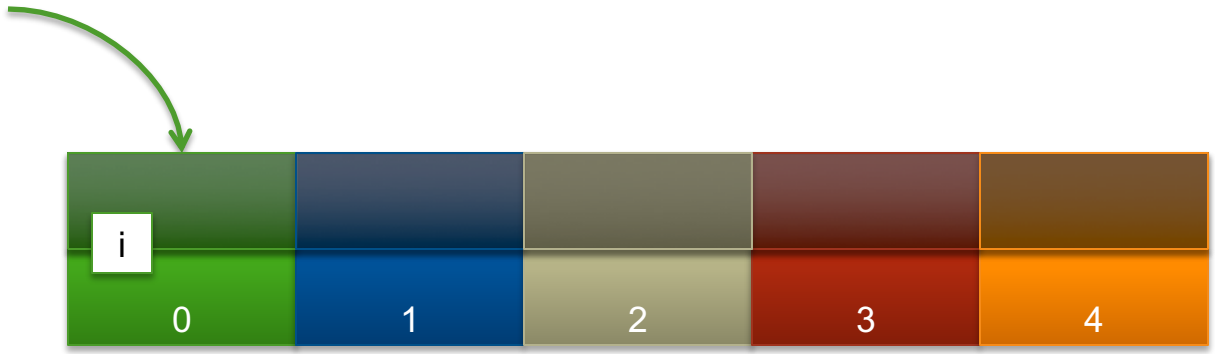
Chapel: Scoping and Locality

```
var i: int;
```



Locales (think: “compute nodes”)

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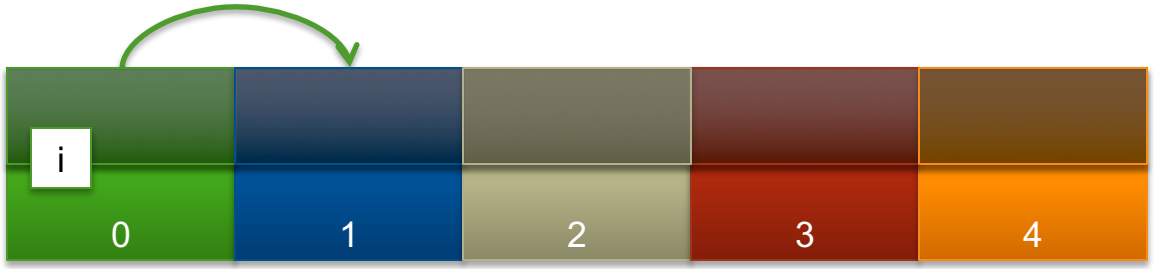
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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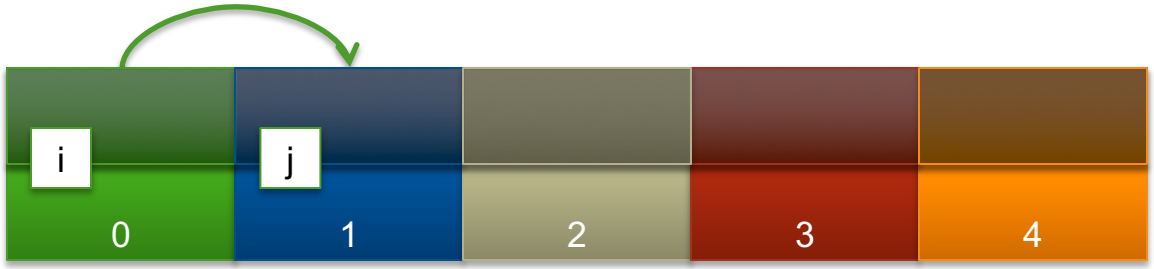
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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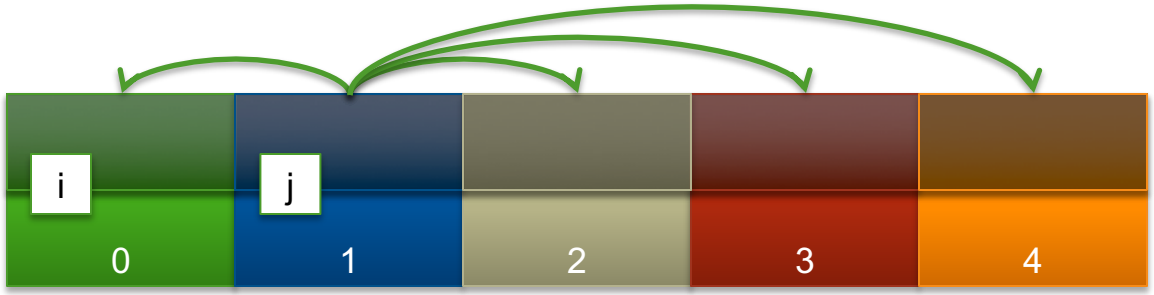
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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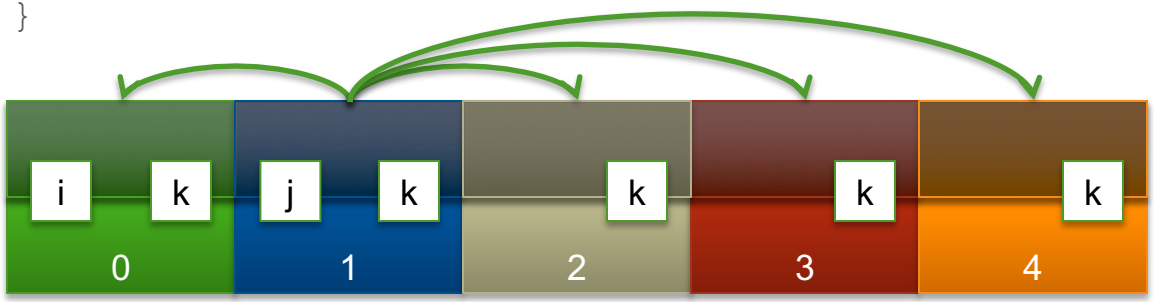
Chapel: Scoping and Locality

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



Locales (think: “compute nodes”)

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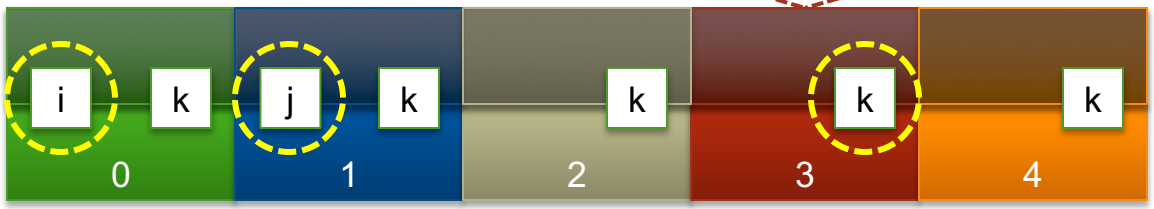
Chapel: Scoping and Locality

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      k = 2*i + j;
    }
  }
}
```

OK to access *i*, *j*, and *k* wherever they live

`k = 2*i + j;`



Locales (think: "compute nodes")

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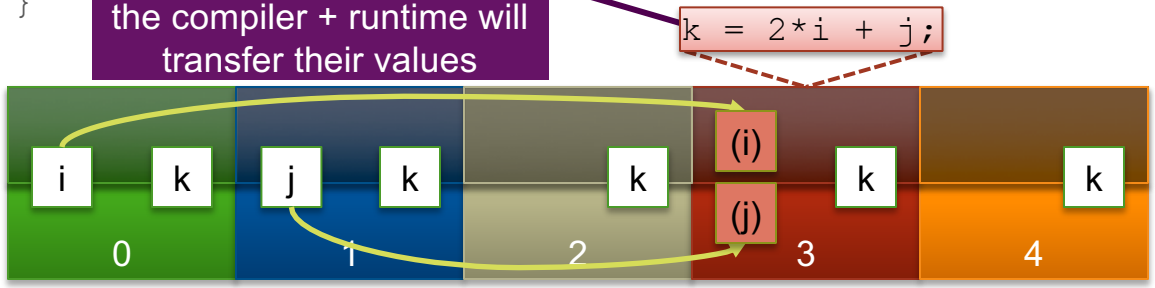
Chapel: Scoping and Locality

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      var k: int;
      k = 2*i + j;
    }
  }
}
```

here, *i* and *j* are remote, so the compiler + runtime will transfer their values



Locales (think: "compute nodes")

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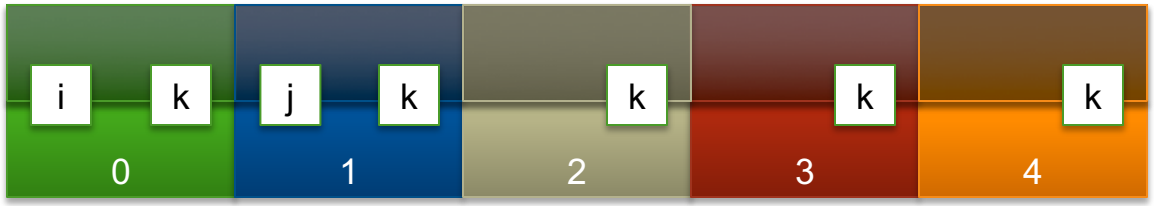
Chapel: Locality queries

```
var i: int;
on Locales[1] {
  var j: int;
  coforall loc in Locales {
    on loc {
      …here…          // query the locale on which this task is running
      …j.locale…      // query the locale on which j is stored
      …here.physicalMemory(…)…  // query system characteristics
      …here.runningTasks()…     // query runtime characteristics
    }
}
```



Locales (think: "compute nodes")

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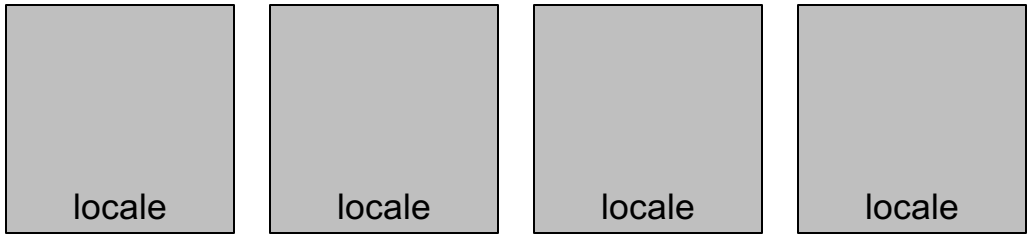
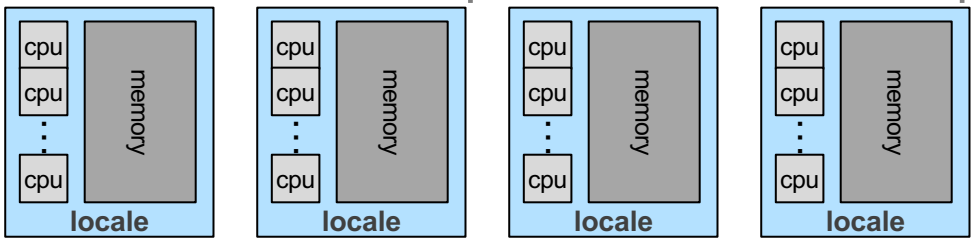
Classic Locales

- **Historically, Chapel's locales were black boxes**
  - Intra-node concerns handled by compiler, runtime, OS



  - This was sufficient when compute nodes were simple



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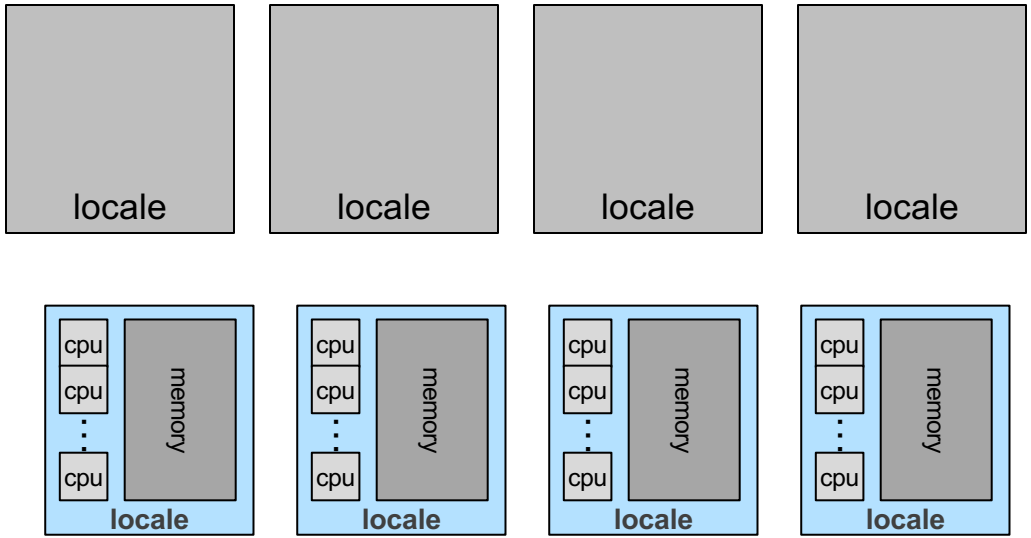
Classic Locales



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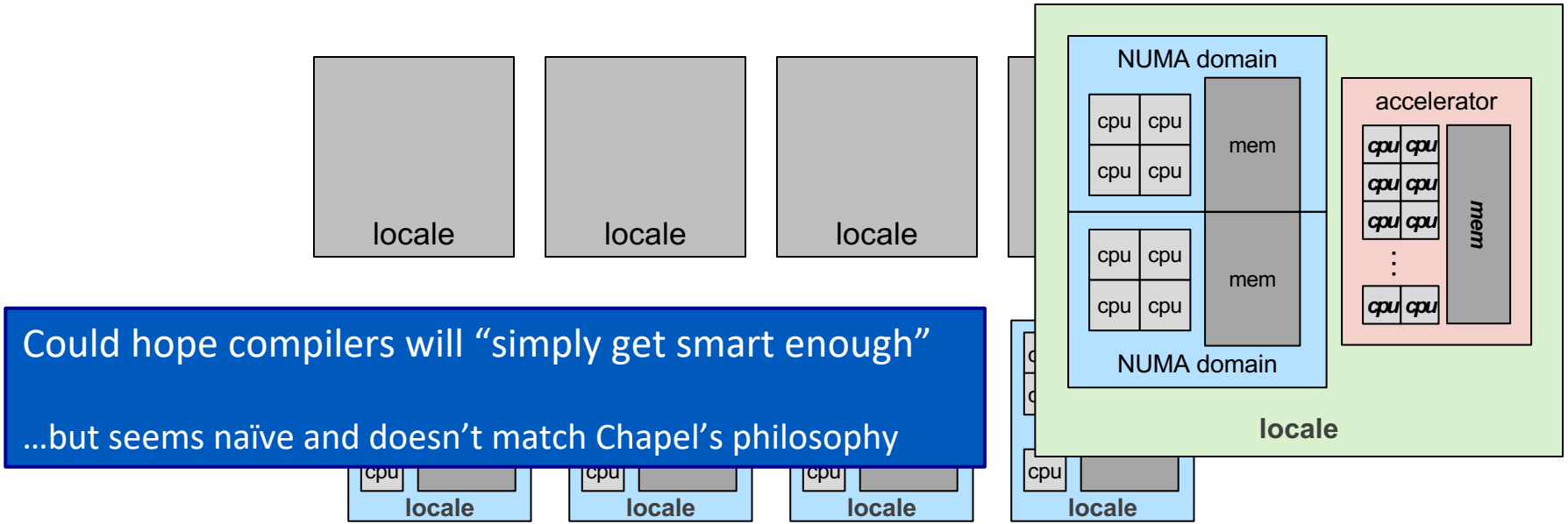
Classic Locales

- **Classic model breaks down for more complex cases**
  - E.g. multiple flavors of memory or processors



Could hope compilers will "simply get smart enough"

…but seems naïve and doesn't match Chapel's philosophy

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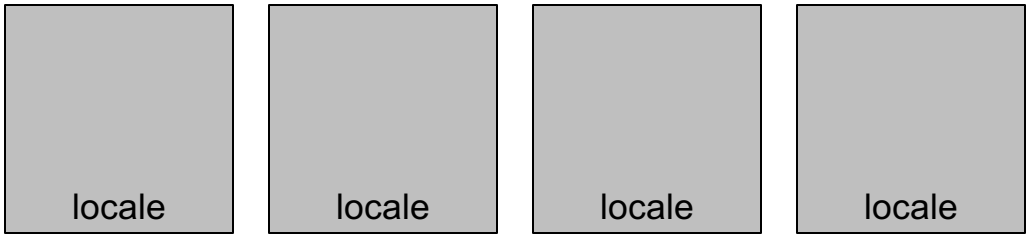
Hierarchical Locales

- So, we made locales hierarchical



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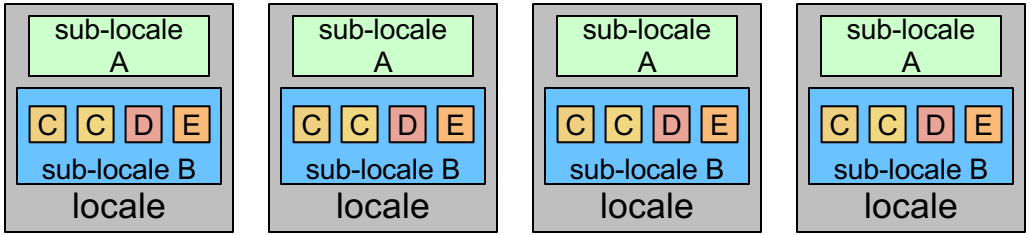
Hierarchical Locales

- **So, we made locales hierarchical**
  - Locales can now themselves contain locales
    - E.g., an accelerator sub-locale, a scratchpad memory sub-locale



  - Target sub-locales with on-clauses, as before

```
on Locales[0].GPU do computationThatLikesGPUs();
```

    - Ideally, hide such logic in abstractions: domain maps, parallel iterators
  - Introduced a new multiresolution type: *locale models*

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Chapel's Locale Models

- **User-specified type representing locales**
- **Similar goals to domain maps:**
  - Support user implementation of key high-level abstractions
  - Make language future-proof (w.r.t. emerging architectures)

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Authoring a Locale Model

- **Creating a locale model:**
  - Create a top-level locale object type
    - In turn, it can contain fields representing sub-locales
  - Each locale / sub-locale type must meet a required interface:
    - **Memory:** How is it managed? (malloc, realloc, free)
    - **Tasking:** How do I launch and synchronize tasks?
    - **Communication:** How are data & control transferred between locales?
      - gets, puts, active messages
      - widening of pointers

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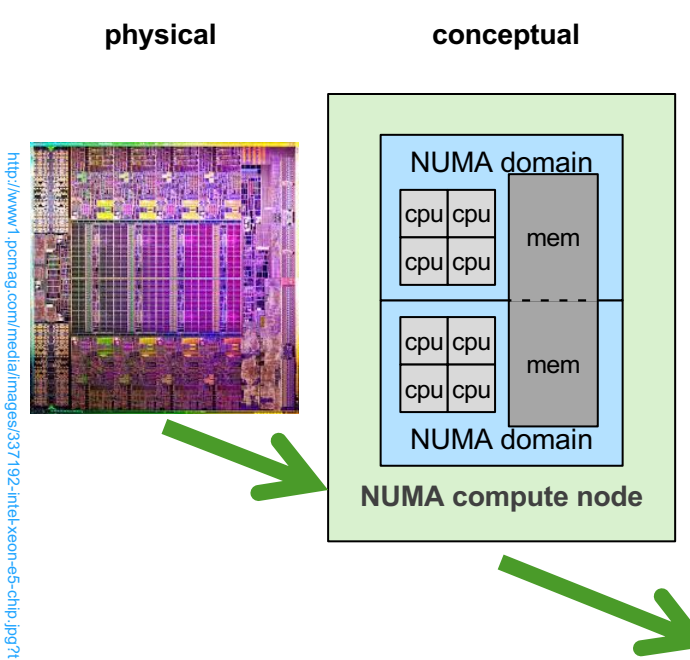
An Example: The numa Locale Model



http://www1.pcmag.com/media/images/337192-intel-xeon-e5-chip.jpg?thumb=y

$CHPL_HOME/modules/…/numa/LocaleModel.chpl

```
class NumaDomain : AbstractLocaleModel {
  const sid: chpl_sublocID_t;
}

// The node model
class LocaleModel : AbstractLocaleModel {
  const numSublocales: int;
  var childSpace: domain(1);
  var childLocales: [childSpace] NumaDomain;
}

// support for memory management
proc chpl_here_alloc(size:int, md:int(16)) { … }

// support for "on" statements
proc chpl_executeOn
     (loc: chpl_localeID_t, // target locale
      fn: int,              // on-body func idx
      args: c_void_ptr,     // func args
      args_size: int(32)    // args size
     ) { … }

// support for tasking stmts: begin, cobegin, coforall
proc chpl_taskListAddCoStmt
     (subloc_id: int,       // target subloc
      fn: int,              // body func idx
      args: c_void_ptr,     // func args
      ref tlist: _task_list, // task list
      tlist_node_id: int    // task list owner
     ) { … }
```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Locale Models: Status

- **All Chapel compilations use a locale model**
  - Set via environment variable or compiler flag
- **Current locale models:**
  - **flat**: the default, has no sublocales (as in the classic model)
  - **numa:** supports a sub-locale per NUMA domain within the node
  - **knl:** for Intel® Xeon Phi™: numa w/ sublocale for HBM/MCDRAM
- **In practice…**
  - we use the 'flat' locale model almost exclusively

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Performance: ‘numa’ vs. ‘flat’

- **Using ‘numa’ leads to performance overheads**
  - Local arrays must be “chunked” between the numa sublocales
  - Indexing must do extra work to pick the right chunk
- **Though ‘flat’ has no sub-locales, it’s also NUMA-aware**
  - First-touch heuristics used to map sub-arrays to NUMA domains
  - Yet array remains contiguous in memory ⇒ simple indexing
- **As a result, ‘numa’ rarely outperforms ‘flat’**

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Challenges: Static analysis & locality

- **Local vs. Remote Locales** (distributed or shared memory?)
  - In general, given:

    ```
    on x.locale …
    ```

    can't statically tell whether locale shares memory with `here` or not
  - May result in overheads due to conservatism
    - "Assuming it's remote, I'll introduce wide pointers & communication, …"

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Challenges: Memory-only locales

- **What if a locale only represents memory? (say)**
  - Have interface run tasks on other locales with processors
    - Choice of policy is up to locale model author
    - Round-robin, dynamic load-balance, nearest, …

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Wrapping Up

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Summary

- **Chapel's design uses a multiresolution philosophy**
  - High-level for productivity
  - Low-level for control
  - User-extensible for flexibility, future-proof design
- **Locale models support mapping to new architectures**
  - Provide bridge from compiler to system resources
  - Enables targeting of heterogeneous resources
- **Chapel performance can match C+MPI+OpenMP**
  - With improvements in readability, writability, code size

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Possible Discussion Topics

- Error-handling / Exceptions

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Chapel Resources

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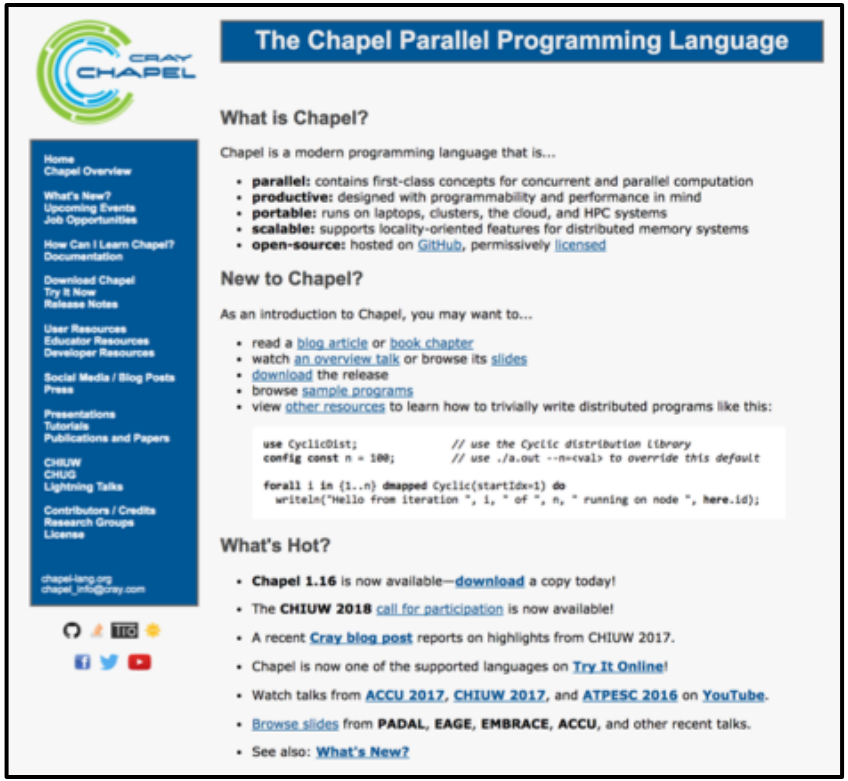
Chapel Central: https://chapel-lang.org/



The Chapel Parallel Programming Language

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chapel-lang.org
chapel_info@cray.com

What is Chapel?

Chapel is a modern programming language that is...

- **parallel:** contains first-class concepts for concurrent and parallel computation
- **productive:** designed with programmability and performance in mind
- **portable:** runs on laptops, clusters, the cloud, and HPC systems
- **scalable:** supports locality-oriented features for distributed memory systems
- **open-source:** hosted on GitHub, permissively licensed

New to Chapel?

As an introduction to Chapel, you may want to...

- read a blog article or book chapter
- watch an overview talk or browse its slides
- download the release
- browse sample programs
- view other resources to learn how to trivially write distributed programs like this:

```
use CyclicDist;              // use the Cyclic distribution library
config const n = 100;        // use ./a.out --n=<val> to override this default

forall i in {1..n} dmapped Cyclic(startIdx=1) do
  writeln("Hello from iteration ", i, " of ", n, " running on node ", here.id);
```

What's Hot?

- **Chapel 1.16** is now available—**download** a copy today!
- The **CHIUW 2018** call for participation is now available!
- A recent **Cray blog post** reports on highlights from CHIUW 2017.
- Chapel is now one of the supported languages on **Try It Online**!
- Watch talks from **ACCU 2017**, **CHIUW 2017**, and **ATPESC 2016** on **YouTube**.
- Browse slides from **PADAL**, **EAGE**, **EMBRACE**, **ACCU**, and other recent talks.
- See also: **What's New?**

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How to Track Chapel

http://facebook.com/ChapelLanguage

http://twitter.com/ChapelLanguage

https://www.youtube.com/channel/UCHmm27bYjhknK5mU7ZzPGsQ/

chapel-announce@lists.sourceforge.net

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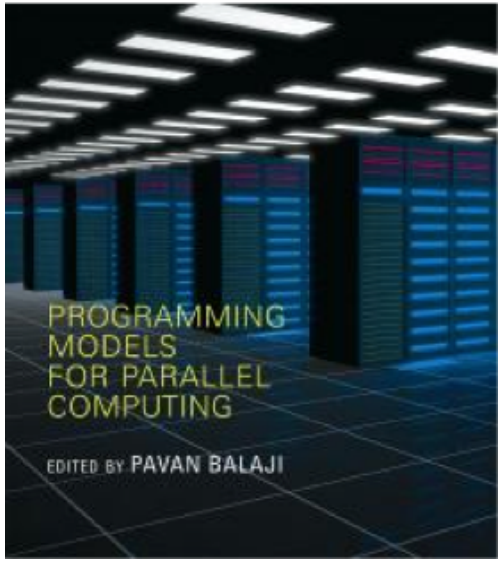
Suggested Reading (healthy attention spans)

Chapel chapter from ***Programming Models for Parallel Computing***

- a detailed overview of Chapel's history, motivating themes, features
- published by MIT Press, November 2015
- edited by Pavan Balaji (Argonne)
- chapter is now also available online



Other Chapel papers/publications available at **https://chapel-lang.org/papers.html**

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Suggested Reading (short attention spans)

CHIUW 2017: Surveying the Chapel Landscape, Cray Blog, July 2017.

- *a run-down of recent events*

Chapel: Productive Parallel Programming, Cray Blog, May 2013.

- *a short-and-sweet introduction to Chapel*

Six Ways to Say "Hello" in Chapel **(parts 1, 2, 3)**, Cray Blog, Sep-Oct 2015.

- *a series of articles illustrating the basics of parallelism and locality in Chapel*

Why Chapel? **(parts 1, 2, 3)**, Cray Blog, Jun-Oct 2014.

- *a series of articles answering common questions about why we are pursuing Chapel in spite of the inherent challenges*

[Ten] Myths About Scalable Programming Languages, IEEE TCSC Blog (index available on chapel-lang.org "blog posts" page), Apr-Nov 2012.

- *a series of technical opinion pieces designed to argue against standard reasons given for not developing high-level parallel languages*

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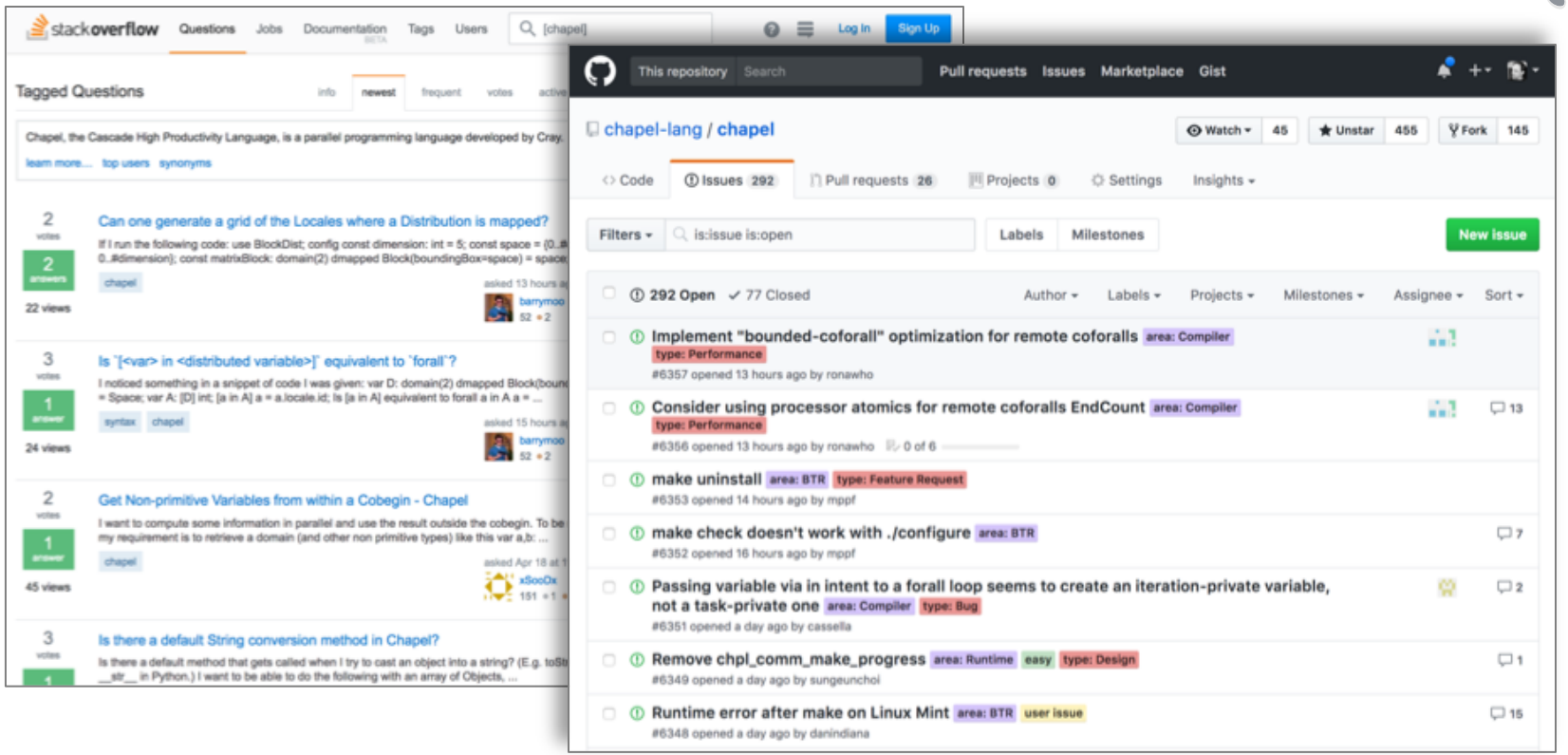
Chapel StackOverflow and GitHub Issues



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Where to..

Submit bug reports:

GitHub issues for chapel-lang/chapel: public bug forum

chapel_bugs@cray.com: for reporting non-public bugs

Ask User-Oriented Questions:

StackOverflow: when appropriate / other users might care

#chapel-users (irc.freenode.net): user-oriented IRC channel

chapel-users@lists.sourceforge.net: user discussions

Discuss Chapel development

chapel-developers@lists.sourceforge.net: developer discussions

#chapel-developers (irc.freenode.net): developer-oriented IRC channel

Discuss Chapel's use in education

chapel-education@lists.sourceforge.net: educator discussions

Directly contact Chapel team at Cray: chapel_info@cray.com

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Questions?

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