Productive Programming in Chapel:
A Computation-Driven Introduction

Base Language with n-body

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Cray Inc,
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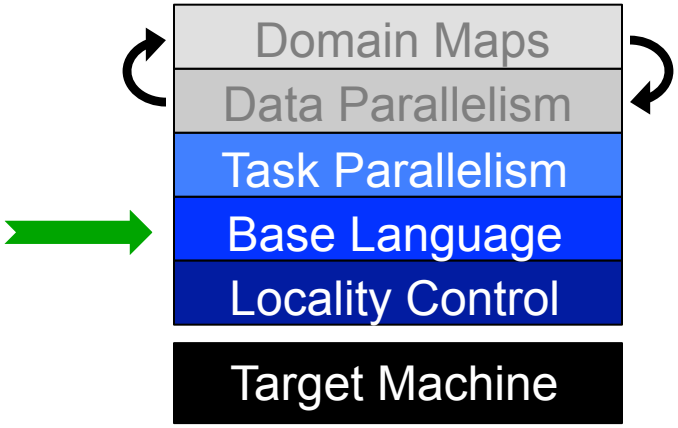
Outline

- ✓ Motivation
- ✓ Chapel Background and Themes
- ➢ Learning the Base Language with n-body
- Short Introduction to Task Parallelism
- Hands-On 1: Hello World
- Short Introduction to Locality
- Data Parallelism with Jacobi
- Hands-On 2: Mandelbrot
- Project Status, Next Steps



Learning Chapel with n-body

n-body in Chapel (where n == 5)

- **A serial computation**
- **From the Computer Language Benchmarks Game**
  - Chapel implementation in release under examples/benchmarks/shootout/nbody.chpl
- **Computes the influence of 5 bodies on one another**
  - The Sun, Jupiter, Saturn, Uranus, Neptune
- **Executes for a user-specifiable number of timesteps**

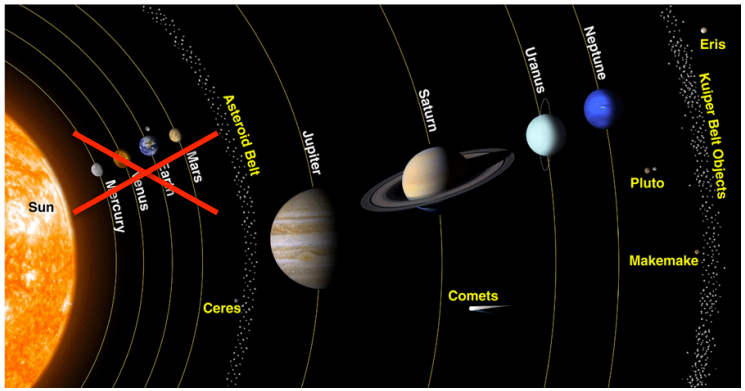


Image source: http://spaceplace.nasa.gov/review/ice-dwarf/solar-system-lrg.png

5-body in Chapel: Declarations

```
const pi = 3.141592653589793,
      solarMass = 4 * pi**2,
      daysPerYear = 365.24;

config const numsteps = 10000;

record body {
  var pos: 3*real;
  var v: 3*real;
  var mass: real;
}


…
```

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…
```

Variable declarations

Configuration Variable

Record declaration

Tuple type

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config const numsteps = 10000;

record body {
  var pos: 3*real;
  var v: 3*real;
  var mass: real;
}

…
```

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Variables, Constants, and Parameters

- **Basic syntax**

```
declaration:
  var   identifier [: type] [= init-expr];
  const identifier [: type] [= init-expr];
  param identifier [: type] [= init-expr];
```

- **Meaning**
  - `var`/`const`: execution-time variable/constant
  - `param`: compile-time constant
  - No *init-expr* ⇒ initial value is the type's default
  - No *type* ⇒ type is taken from *init-expr*
- **Examples**

```
const pi: real = 3.14159;
var count: int;              // initialized to 0
param debug = true;          // inferred to be bool
```

Aside: Static Type Inference

```
const pi = 3.14,              // pi is a real
      coord = 1.2 + 3.4i,     // coord is a complex…
      coord2 = pi*coord,      // …as is coord2
      name = "brad",          // name is a string
      verbose = false;        // verbose is boolean

proc addem(x, y) {            // addem() has generic arguments
  return x + y;               //   and an inferred return type
}

var sum = addem(1, pi),                  // sum is a real
    fullname = addem(name, "ford");      // fullname is a string

writeln((sum, fullname));
```

```
(4.14, bradford)
```

5-body in Chapel: Declarations

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      daysPerYear = 365.24;

config const numsteps = 10000;

record body {
  var pos: 3*real;
  var v: 3*real;
  var mass: real;
}

…
```

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const pi = 3.141592653589793,
      solarMass = 4 * pi**2,
      daysPerYear = 365.24;

config const numsteps = 10000;

record body {
  var pos: 3*real;
  var v: 3*real;
  var mass: real;
}


…
```

Configuration Variable

```
$ ./nbody --numsteps=100
```

Configs

```
param intSize = 32;
type elementType = real(32);
const epsilon = 0.01:elementType;
var start = 1:int(intSize);
```

Configs

```
config param intSize = 32;
config type elementType = real(32);
config const epsilon = 0.01:elementType;
config var start = 1:int(intSize);
```

```
$ chpl myProgram.chpl -sintSize=64 -selementType=real
$ ./a.out --start=2 --epsilon=0.00001
```

5-body in Chapel: Declarations

```
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      solarMass = 4 * pi**2,
      daysPerYear = 365.24;

config const numsteps = 10000;

record body {
  var pos: 3*real;
  var v: 3*real;
  var mass: real;
}

…
```

Variable declarations

Configuration Variable

Record declaration

Tuple type

Records and Classes

- **Chapel's struct/object types**
  - Contain variable definitions (fields)
  - Contain procedure & iterator definitions (methods)
  - Records: value-based (*e.g.*, assignment copies fields)
  - Classes: reference-based (*e.g.*, assignment aliases object)
  - Record : Class :: C++ struct : Java class

- **Example**

```
record circle {
  var radius: real;
  proc area() {
    return pi*radius**2;
  }
}
```

```
var c1, c2: circle;
c1 = new circle(radius=1.0);
c2 = c1;              // copies c1
c1.radius = 5.0;
writeln(c2.radius);   // 1.0
// records deleted by compiler
```

Records and Classes

- **Chapel's struct/object types**
  - Contain variable definitions (fields)
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  - Records: value-based (*e.g.*, assignment copies fields)
  - Classes: reference-based (*e.g.*, assignment aliases object)
  - Record : Class :: C++ struct : Java class

- **Example**

```
class circle {
  var radius: real;
  proc area() {
    return pi*radius**2;
  }
}
```

```
var c1, c2: circle;
c1 = new circle(radius=1.0);
c2 = c1;  // aliases c1's circle
c1.radius = 5.0;
writeln(c2.radius);  // 5.0
delete c1; // users delete classes
```

5-body in Chapel: Declarations

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const pi = 3.141592653589793,
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      daysPerYear = 365.24;

config const numsteps = 10000;

record body {
  var pos: 3*real;
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  var mass: real;
}

…
```

Variable declarations

Configuration Variable

Record declaration

Tuple type

Tuples

- **Use**
  - support lightweight grouping of values
    - e.g., passing/returning procedure arguments
    - multidimensional array indices
    - short vectors

- **Examples**

```
var coord: (int, int, int) = (1, 2, 3);
var coordCopy: 3*int = coord;
var (i1, i2, i3) = coord;
var triple: (int, string, real) = (7, "eight", 9.0);
```

5-body in Chapel: Declarations

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record body {
  var pos: 3*real;
  var v: 3*real;
  var mass: real;
}

…
```

Variable declarations

Configuration Variable

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Tuple type

5-body in Chapel: the Bodies

```
var bodies =
    [  /* sun */
       new body(mass = solarMass),

       /* jupiter */
       new body(pos = ( 4.8414314424647209e+00,
                       -1.1603200440274284e+00,
                       -1.0362204447112310e-01),
                  v = ( 1.6600766427440369e-03 * daysPerYear,
                        7.6990111841974042e-03 * daysPerYear,
                       -6.9046001697206302e-05 * daysPerYear),
               mass =   9.5479193842432661e-04 * solarMass),

       /* saturn */
       new body(…),

       /* uranus */
       new body(…),

       /* neptune */
       new body(…)
    ]
```

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```

Creating a Record

Tuples

Array

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Tuples

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       /* saturn */
       new body(…),

       /* uranus */
       new body(…),

       /* neptune */
       new body(…)
    ]
```

Creating a Record

Tuples

Array

Array Types

- **Syntax**

```
array-type:
  [ domain-expr ] elt-type
array-value:
  [elt1, elt2, elt3, … eltn]
```

- **Meaning:**
  - array-type: stores an element of *elt-type* for each index
  - array-value: represent the array with these values
- **Examples**

```
var A: [1..3] int,                  // A stores 0, 0, 0
    B = [5, 3, 9],                  // B stores 5, 3, 9
    C: [1..m, 1..n] real,           // 2D m by n array of reals
    D: [1..m][1..n] real;           // array of arrays of reals
```

Much more on arrays in data parallelism section later…

5-body in Chapel: the Bodies

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       /* saturn */
       new body(…),

       /* uranus */
       new body(…),

       /* neptune */
       new body(…)
    ]
```

Creating a Record

Tuples

Array

5-body in Chapel: main()

```
…

proc main() {
  initSun();

  writef("%.9r\n", energy());
  for 1..numsteps do
    advance(0.01);
  writef("%.9r\n", energy());
}

…
```

5-body in Chapel: main()

```
…

proc main() {
  initSun();

  writef("%.9r\n", energy());
  for 1..numsteps do
    advance(0.01);
  writef("%.9r\n", energy());
}

…
```

Procedure Definition

Procedure Call

Formatted I/O
*not covered here

Looping over a Range

5-body in Chapel: main()

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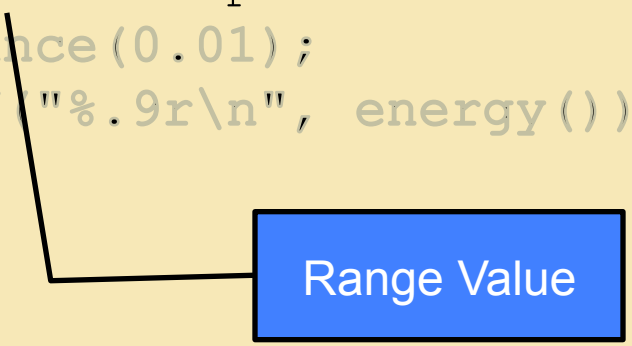

Range Values

- **Syntax**

```
range-expr:
  [low] .. [high]
```

- **Semantics**
  - Regular sequence of integers
    low <= high: *low*, *low*+1, *low*+2, …, *high*
    low > *high*: degenerate (an empty range)
    low or *high* unspecified: unbounded in that direction
- **Examples**

```
1..6              // 1, 2, 3, 4, 5, 6
6..1              // empty
3..               // 3, 4, 5, 6, 7, …
```

Range Types and Algebra

```
const r = 1..10;

printVals(r);
printVals(0.. #n);
printVals(r # 3);
printVals(r by 2);
printVals(r by -2);
printVals(r by 2 # 3);
printVals(r # 3 by 2);

proc printVals(r) {
  for i in r do
    write(i, " ");
  writeln();
}
```

```
1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 … n-1
1 2 3
1 3 5 7 9
10 8 6 4 2
1 3 5
1 3
```

5-body in Chapel: main()

```
…

proc main() {
  initSun();

  writef("%.9r\n", energy());
  for 1..numsteps do
    advance(0.01);
  writef("%.9r\n", energy());
}

…
```

Procedure Definition

Procedure Call

Formatted I/O
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Looping over a Range

For Loops

- **Syntax:**

```
for-loop:
  for [index-expr in] iteratable-expr { stmt-list }
```

- **Meaning:**
  - Executes loop body serially, once per loop iteration
  - Declares new variables for identifiers in *index-expr*
    - type and const-ness determined by *iteratable-expr*
    - *iteratable-expr* could be a range, array, or iterator

- **Examples**

```
var A: [1..3] string = [" DO", " RE", " MI"];

for i in 1..3 { write(A[i]); }          // DO RE MI
for a in A { a += "LA"; } write(A);     // DOLA RELA MILA
```

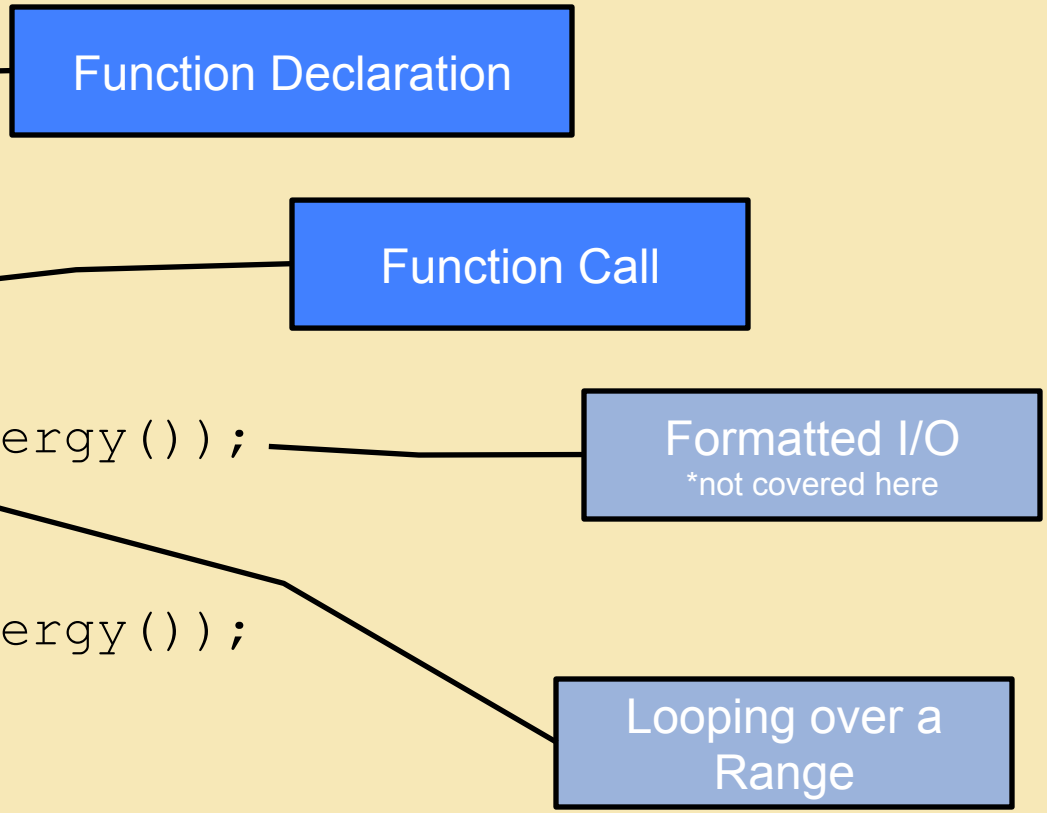
5-body in Chapel: main()

```
…

proc main() {
  initSun();

  writef("%.9r\n", energy());
  for 1..numsteps do
    advance(0.01);
  writef("%.9r\n", energy());
}

…
```



5-body in Chapel: advance()

```
 advance(0.01);
…
proc advance(dt) {
  for i in 1..numbodies {
    for j in i+1..numbodies {
      const dpos = bodies[i].pos - bodies[j].pos,
            mag = dt / sqrt(sumOfSquares(dpos))**3;

      bodies[i].v -= dpos * bodies[j].mass * mag;
      bodies[j].v += dpos * bodies[i].mass * mag;
    }
  }

  for b in bodies do
    b.pos += dt * b.v;
}
```

5-body in Chapel: advance()

```
 advance(0.01);
…
proc advance(dt) {
  for i in 1..numbodies {
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      const dpos = bodies[i].pos - bodies[j].pos,
            mag = dt / sqrt(sumOfSquares(dpos))**3;

      bodies[i].v -= dpos * bodies[j].mass * mag;
      bodies[j].v += dpos * bodies[i].mass * mag;
    }
  }

  for b in bodies do
    b.pos += dt * b.v;
}
```

$$m_1\mathbf{a}_1 = \frac{Gm_1m_2}{r_{12}^3}(\mathbf{r}_2 - \mathbf{r}_1) \quad \text{Sun-Earth}$$

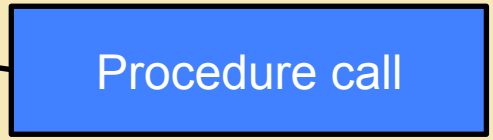
$$m_2\mathbf{a}_2 = \frac{Gm_1m_2}{r_{21}^3}(\mathbf{r}_1 - \mathbf{r}_2) \quad \text{Earth-Sun}$$

5-body in Chapel: advance()

```
 advance(0.01);
…
proc advance(dt) {
  for i in 1..numbodies {
    for j in i+1..numbodies {
      const dpos = bodies[i].pos - bodies[j].pos,
                 mag = dt / sqrt(sumOfSquares(dpos))**3;

      bodies[i].v -= dpos * bodies[j].mass * mag;
      bodies[j].v += dpos * bodies[i].mass * mag;
    }
  }

  for b in bodies do
    b.pos += dt * b.v;
}
```



Procedures, by example

- Example to compute the area of a circle

```
proc area(radius: real): real {
  return 3.14 * radius**2;
}

writeln(area(2.0));  // 12.56
```

```
proc area(radius) {
  return 3.14 * radius**2;
}
```

Argument and return types can be omitted

- Example of argument default values, naming

```
proc writeCoord(x: real = 0.0, y: real = 0.0) {
  writeln((x,y));
}

writeCoord(2.0);          // (2.0, 0.0)
writeCoord(y=2.0);        // (0.0, 2.0)
writeCoord(y=2.0, 3.0); // (3.0, 2.0)
```

5-body in Chapel: advance() using references

```
proc advance(dt) {
  for i in 1..numbodies {
    for j in i+1..numbodies {
      ref bi = bodies[i],
          bj = bodies[j];

      const dpos = bi.pos - bj.pos,
            mag = dt / sqrt(sumOfSquares(dpos))**3;

      bi.v -= dpos * bj.mass * mag;
      bj.v += dpos * bi.mass * mag;
    }
  }

  for b in bodies do
    b.pos += dt * b.v;
}
```

Reference declarations

Reference Declarations

- **Syntax:**

```
ref-decl:
  ref ident = expr;
```

- **Meaning:**
  - Causes 'ident' to refer to variable specified by 'expr'
  - Subsequent reads/writes of 'ident' refer to that variable
  - Not a pointer: no way to reference something else with 'ident'
  - Similar to a C++ reference

- **Examples**

```
var A: [1..3] string = [" DO", " RE", " MI"];
ref a2 = A[2];
a2 = " YO";
for i in 1..3 { write(A(i)); }          // DO YO MI
```

5-body in Chapel: advance() using references

```
proc advance(dt) {
  for i in 1..numbodies {
    for j in i+1..numbodies {
      ref bi = bodies[i],
          bj = bodies[j];

      const dpos = bi.pos - bj.pos,
            mag = dt / sqrt(sumOfSquares(dpos))**3;

      bi.v -= dpos * bj.mass * mag;
      bj.v += dpos * bi.mass * mag;
    }
  }

  for b in bodies do
    b.pos += dt * b.v;
}
```

Reference declarations

5-body in Chapel: Using Iterators

```
iter triangle(n) {
  for i in 1..n do
    for j in i+1..n do
      yield (i,j);
}

proc advance(dt) {
  for (i,j) in triangle(numbodies) {
    const dpos = bodies[i].pos - bodies[j].pos,
          mag = dt / sqrt(sumOfSquares(dpos))**3;

    …
  }
…
}
…
```

Definition of iterator

Use of iterator

Iterators

```
iter fibonacci(n) {
  var current = 0,
      next = 1;
  for 1..n {
    yield current;
    current += next;
    current <=> next;
  }
}
```

```
for f in fibonacci(7) do
  writeln(f);
```

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

```
iter tiledRMO(D, tilesize) {
  const tile = {0..#tilesize,
                0..#tilesize};
  for base in D by tilesize do
    for ij in D[tile + base] do
      yield ij;
}
```

```
for ij in tiledRMO({1..m, 1..n}, 2) do
  write(ij);
```

```
(1,1) (1,2) (2,1) (2,2)
(1,3) (1,4) (2,3) (2,4)
(1,5) (1,6) (2,5) (2,6)
…
(3,1) (3,2) (4,1) (4,2)
```

Zippered Iteration

```
for (i,f) in zip(0..#n, fibonacci(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
…
```

Other Base Language Features

- rank-independent programming features
- interoperability features
- compile-time features for meta-programming
  - e.g., compile-time functions to compute types, parameters
- argument intents
- overloading, where clauses
- modules (for namespace management)
- …

Questions about the Base Language?

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