Base Language

Outline: High-Level Feature Survey

- **Running example: naïve n-body computation**
  - Simple declarations
  - Records and Classes
  - Tuples
  - Arrays
  - Ranges: Integer Sequences
  - Basic Serial Control Flow
  - Subroutines: Procedures and Iterators
  - Reference Variables

Outline: Additional Details

- Type Aliases and Casts
- Enums
- Modules and Use Statements
- More on Procedures, Iterators, and Methods
- Generics and Compile-Time Computation
- Special Subroutine Forms
- Initializers for Records and Classes
- Class Instance Memory Management
- Error-Handling
- Error-Handling and Parallelism
- Defer Statements
- Interoperation

Running Example: naïve n-body computation

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**

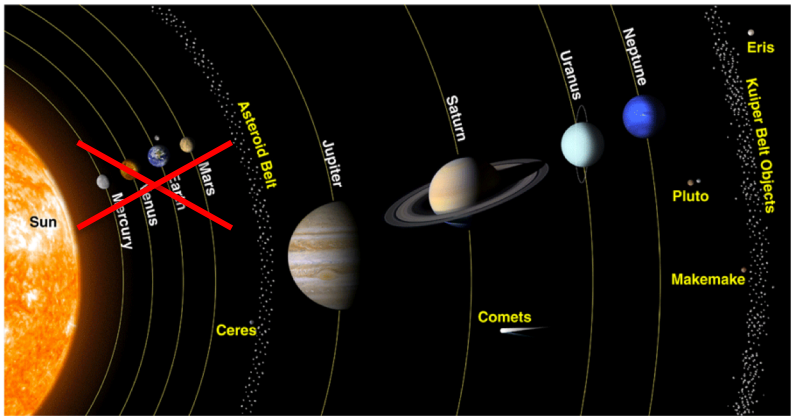


Image source: http://spaceplace.nasa.gov/review/ice-dwarf/solar-system-lrg.png

Simple Declarations

5-body in Chapel: Declarations

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

Variable declarations

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
```

Primitive Types

Type	Description	Default Value	Currently-Supported Bit Widths	Default Bit Width
bool	logical value	false	8, 16, 32, 64	impl. dep.
int	signed integer	0	8, 16, 32, 64	64
uint	unsigned integer	0	8, 16, 32, 64	64
real	real floating point	0.0	32, 64	64
imag	imaginary floating point	0.0i	32, 64	64
complex	complex floating points	0.0 + 0.0i	64, 128	128
string	character string	""	N/A	N/A

- **Syntax**

```
primitive-type:
   type-name [( bit-width )]
```

- **Examples**

```
int(16)   // 16-bit int
real(32)  // 32-bit real
uint      // 64-bit uint
```

Chapel's 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)
```

Basic Operators and Precedence

Operator	Description	Associativity	Overloadable
`:`	cast	left	no
`**`	exponentiation	right	yes
`! ~`	logical and bitwise negation	right	yes
`* / %`	multiplication, division and modulus	left	yes
(unary) `+ -`	positive identity and negation	right	yes
`<< >>`	shift left and shift right	left	yes
`&`	bitwise/logical and	left	yes
`^`	bitwise/logical xor	left	yes
`|`	bitwise/logical or	left	yes
`+ -`	addition and subtraction	left	yes
`<= >= < >`	ordered comparison	left	yes
`== !=`	equality comparison	left	yes
`&&`	short-circuiting logical and	left	via `isTrue`
`||`	short-circuiting logical or	left	via `isTrue`

5-body in Chapel: Declarations

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

Variable declarations

5-body in Chapel: Declarations

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

config const numsteps = 10000;
```

Configuration Variable

5-body in Chapel: Declarations

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

config const numsteps = 10000;
```

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
$ ./myProgram--start=2 --epsilon=0.00001
```

5-body in Chapel: Declarations

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

config const numsteps = 10000;
```

Configuration Variable

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;
}


…
```

Record declaration

Records and Classes

Records and Classes

- **Chapel's 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)

- **Example**

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

```
var c1: circle; // default-initialized
c1 = new circle(radius=1.0);
var c2 = c1;     // copies c1
c1.radius = 5.0;
writeln(c2.radius);   // prints 1.0
```

Records and Classes

- **Chapel's 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)

- **Example**

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

```
var c1: circle; // initially nil
c1 = new circle(radius=1.0);
var c2 = c1;     // aliases c1's circle
c1.radius = 5.0;
writeln(c2.radius);   // prints 5.0
```

Classes vs. Records

Classes

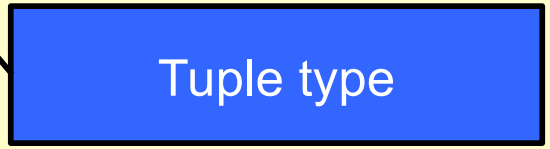
- **heap-allocated**
  - Variables point to objects
  - Objects could be anywhere
  - Support mem. mgmt. policies
- **‘reference' semantics**
  - compiler will only copy pointers
- **support inheritance**
- **support dynamic dispatch**
- **identity matters most**
- **similar to Java classes**

Records

- **allocated in-place**
  - Variables are the objects
  - Objects are “right here”
  - Always freed at end of scope
- **'value' semantics**
  - compiler may introduce copies
- **no inheritance**
- **no dynamic dispatch**
- **value matters most**
- **similar to C++ structs**
  - (sans pointers)

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;
}


…
```



Tuples

Tuples

- **Use**
  - support lightweight grouping of values
    - e.g., passing/returning multiple procedure arguments at once
    - short vectors
    - multidimensional array indices
  - support heterogeneous data types

- **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

```
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;
}


…
```

Variable declarations

Configuration Variable

Record declaration

Tuple type

5-body in Chapel: the Bodies

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

       /* jupiter */
       new body(pos = ( 4.84143144246472090e+00,
                       -1.16032004402742839e+00,
                       -1.03622044471123109e-01),
                  v = ( 1.66007664274403694e-03 * daysPerYear,
                        7.69901118419740425e-03 * daysPerYear,
                       -6.90460016972063023e-05 * daysPerYear),
               mass =   9.54791938424326609e-04 * solarMass),

       /* saturn */
       new body(…),

       /* uranus */
       new body(…),

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

5-body in Chapel: the Bodies

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

       /* jupiter */
       new body(pos = ( 4.84143144246472090e+00,
                       -1.16032004402742839e+00,
                       -1.03622044471123109e-01),
                  v = ( 1.66007664274403694e-03 * daysPerYear,
                        7.69901118419740425e-03 * daysPerYear,
                       -6.90460016972063023e-05 * daysPerYear),
               mass =   9.54791938424326609e-04 * solarMass),

       /* saturn */
       new body(…),

       /* uranus */
       new body(…),

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

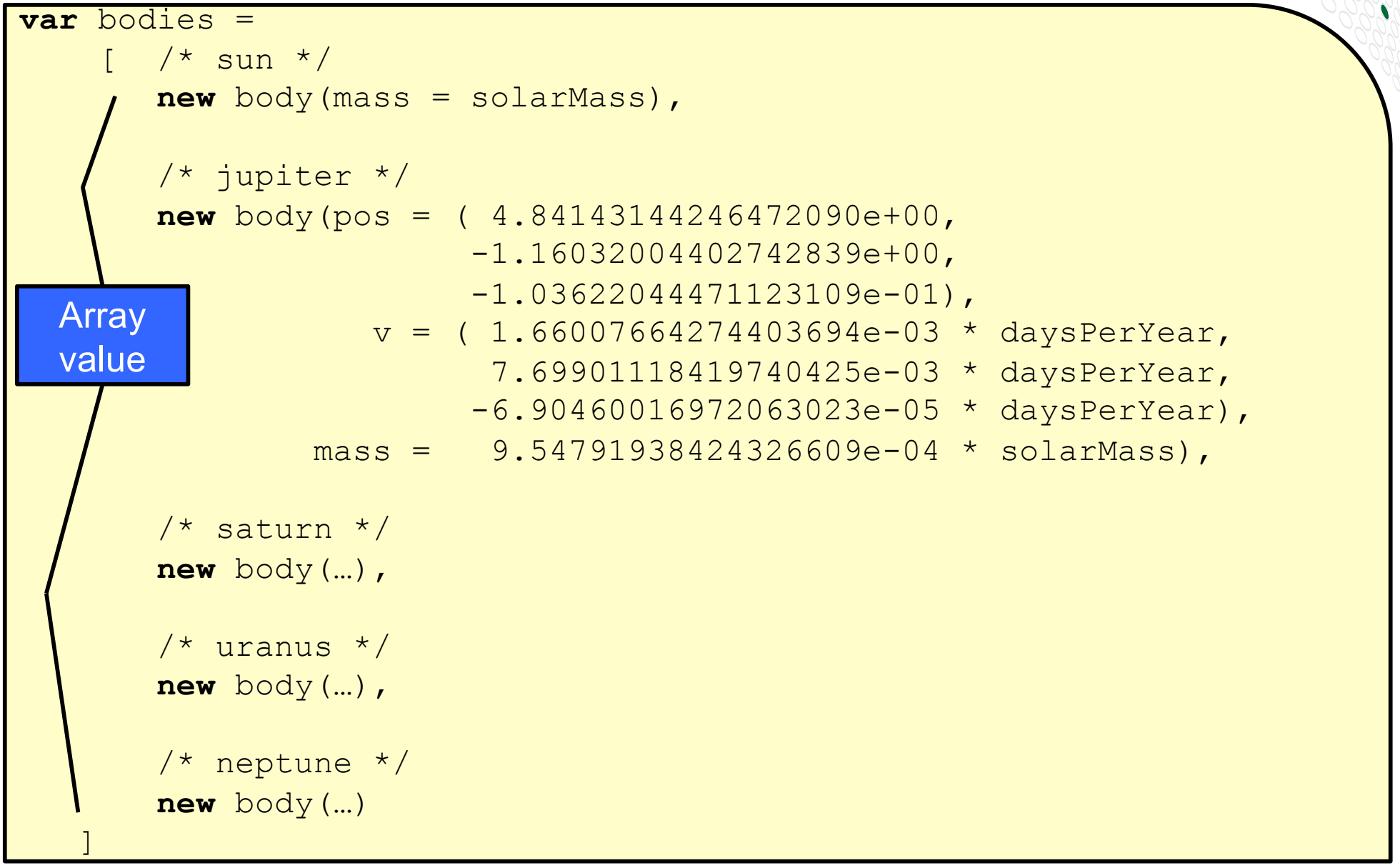
Create a record object

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(…)
    ]
```

Tuple values

5-body in Chapel: the Bodies




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

       /* jupiter */
       new body(pos = ( 4.84143144246472090e+00,
                       -1.16032004402742839e+00,
                       -1.03622044471123109e-01),
                  v = ( 1.66007664274403694e-03 * daysPerYear,
                        7.69901118419740425e-03 * daysPerYear,
                       -6.90460016972063023e-05 * daysPerYear),
                mass =   9.54791938424326609e-04 * solarMass),

       /* saturn */
       new body(…),

       /* uranus */
       new body(…),

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

Arrays

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

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

       /* jupiter */
       new body(pos = ( 4.84143144246472090e+00,
                       -1.16032004402742839e+00,
                       -1.03622044471123109e-01),
                  v = ( 1.66007664274403694e-03 * daysPerYear,
                        7.69901118419740425e-03 * daysPerYear,
                       -6.90460016972063023e-05 * daysPerYear),
                mass =   9.54791938424326609e-04 * solarMass),

       /* saturn */
       new body(…),

       /* uranus */
       new body(…),

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

Create a record object

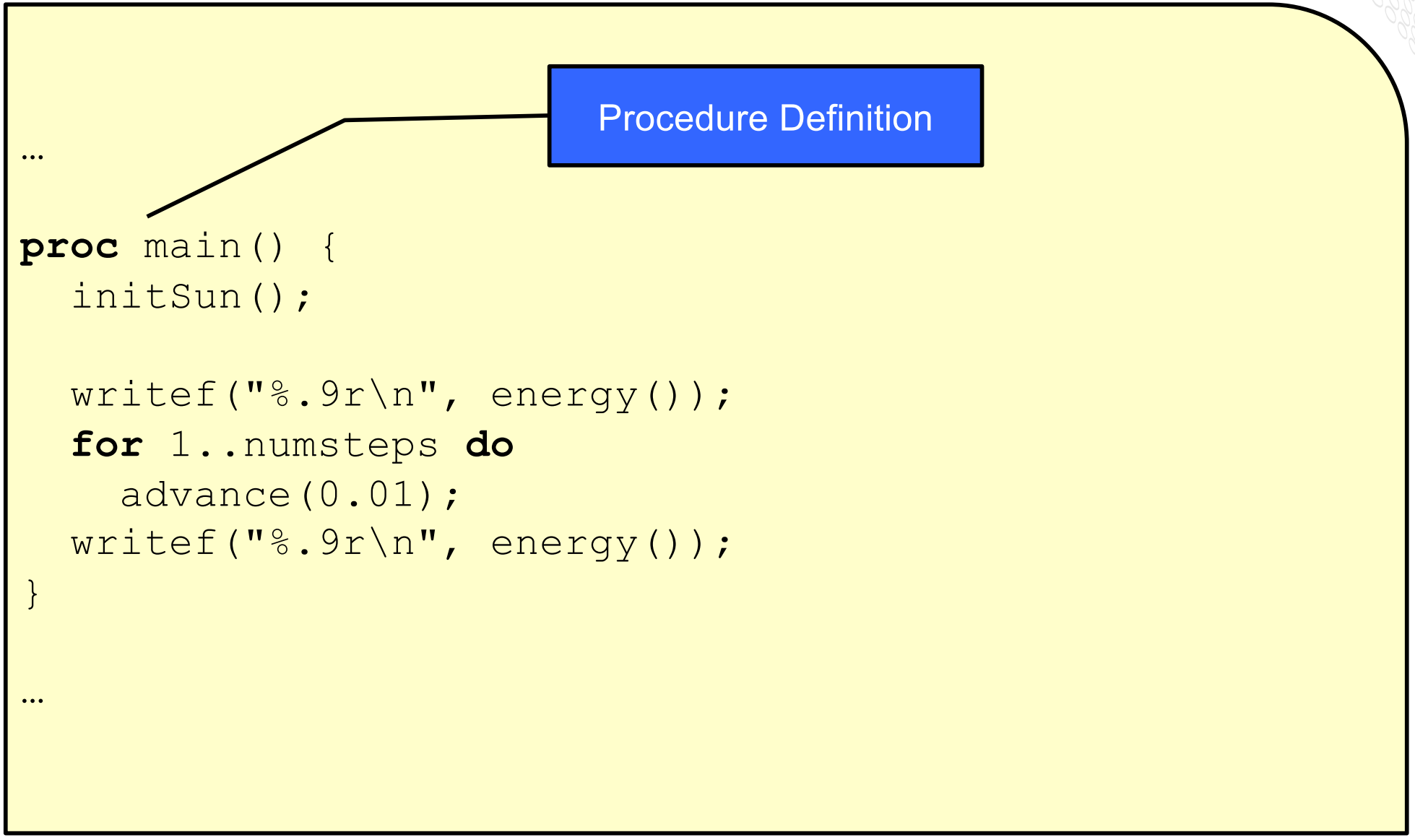
Tuple values

Array value

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()



5-body in Chapel: main()

```
…

proc main() {
  initSun();

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

…
```

Procedure Call

5-body in Chapel: main()

```
…

proc main() {
  initSun();

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

…
```

Formatted I/O

5-body in Chapel: main()

```
…

proc main() {
  initSun();

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

…
```

Range Value

Ranges: Integer Sequences

Range Values

- **Syntax**

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

- **Definition**
  - 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 Operators

```
const r = 1..10;

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

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

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

5-body in Chapel: main()

```
…

proc main() {
  initSun();

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

…
```

Serial for loop

Basic Serial Control Flow

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, iterator, iterable object, …

- **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
```

Control Flow: Other Forms

- Conditional statements

```
if cond { computeA(); } else { computeB(); }
```

- While loops

```
while cond {
  compute();
}
```

- For loops

```
for indices in iteratable-expr {
  compute();
}
```

- Select statements

```
select key {
  when value1 { compute1(); }
  when value2 { compute2(); }
  otherwise   { compute3(); }
}
```

Control Flow: Braces vs. Keywords

Control flow statements specify bodies using curly brackets (compound statements)

- Conditional statements

```
if cond { computeA(); } else { computeB(); }
```

- While loops

```
while cond {
  compute();
}
```

- For loops

```
for indices in iteratable-expr {
  compute();
}
```

- Select statements

```
select key {
  when value1 { compute1(); }
  when value2 { compute2(); }
  otherwise   { compute3(); }
}
```

Control Flow: Braces vs. Keywords

They also support keyword-based forms for single-statement cases

- Conditional statements

```
if cond then computeA(); else computeB();
```

- While loops

```
while cond do
  compute();
```

- For loops

```
for indices in iteratable-expr do
  compute();
```

- Select statements

```
select key {
  when value1 do compute1();
  when value2 do compute2();
  otherwise   do compute3();
}
```

Control Flow: Braces vs. Keywords

Of course, since compound statements are single statements, the two forms can be mixed…

- Conditional statements

```
if cond then { computeA(); } else { computeB(); }
```

- While loops

```
while cond do {
  compute();
}
```

- For loops

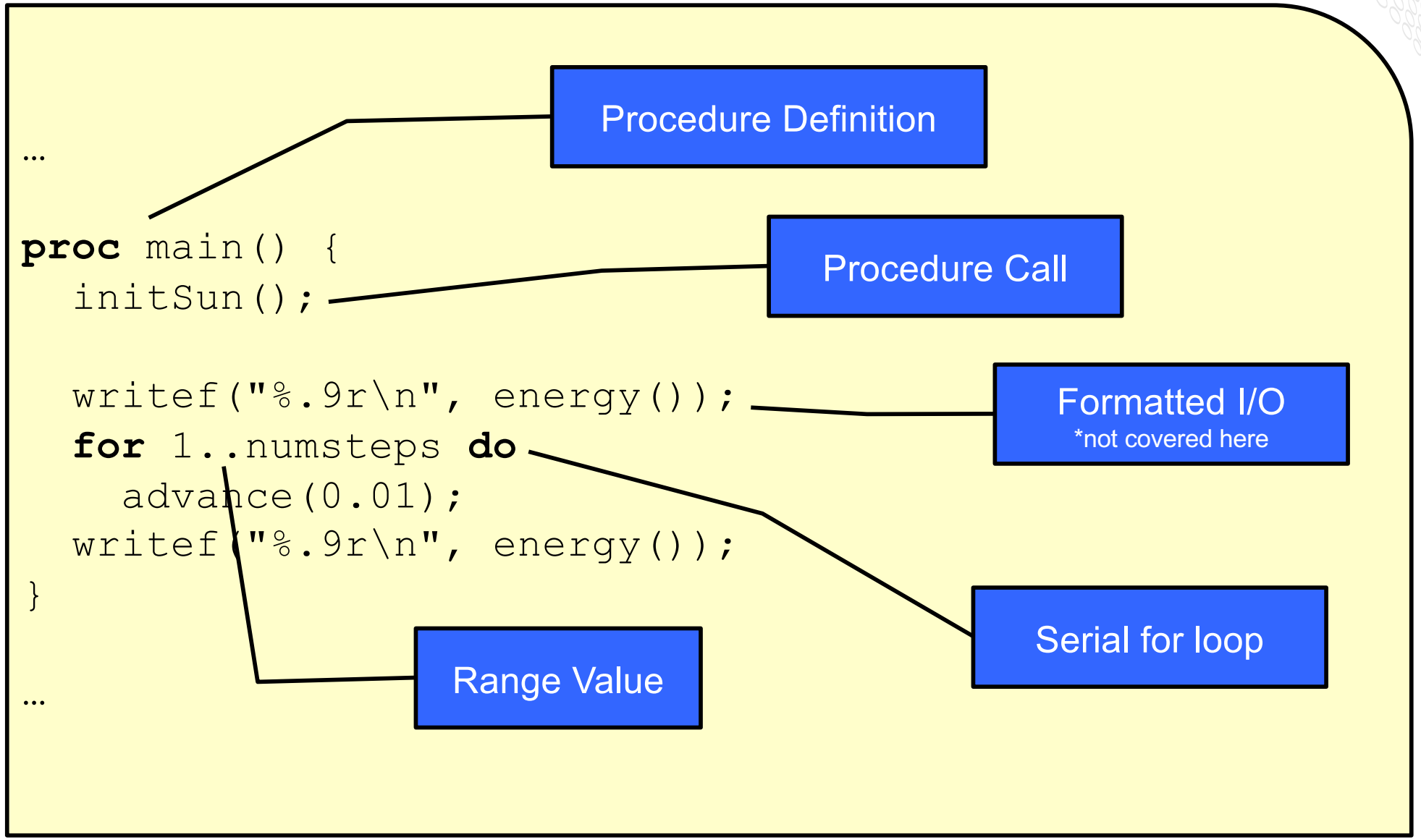
```
for indices in iteratable-expr do {
  compute();
}
```

- Select statements

```
select key {
  when value1 do { compute1(); }
  when value2 do { compute2(); }
  otherwise   do { compute3(); }
}
```

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 {
    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;
}
```

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

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

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;
}
```

Procedure call

Procedure definition

Subroutines: Procedures and Iterators

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)
```

Argument Intents

- **Arguments can optionally be given intents**
  - (blank): varies with type; follows principle of least surprise
    - most types: `const in` or `const ref`
    - arrays, sync/single vars, atomics: `ref`
  - `in`: initializes formal using actual; permits formal to be modified
  - `out`: copies formal into actual at procedure return
  - `inout`: does both of the above
  - `ref`: formal is a reference back to the actual
  - `const` [`ref` | `in`]: disallows modification of the formal
  - `param`/`type`: actual must be a param/type

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(x: real, y: [] real) {
  // x = 1.2;   // illegal: scalars are passed 'const in' by default
  y = 3.4;   // OK: arrays are passed 'ref' by default
}

var r: real,
    A: [1..3] real;

foo(r, A);

writeln((r, A));   // writes (0.0, [3.4, 3.4, 3.4])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(in x: real, in y: [] real) {
  x = 1.2;   // OK: local copy is modified
  y = 3.4;   // OK: local copy is modified
}

var r: real,
    A: [1..3] real;

foo(r, A);

writeln((r, A));   // writes (0.0, [0.0, 0.0, 0.0])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(out x: real, out y: [] real) {
  x = 1.2;   // OK: local copy is modified
  y = 3.4;   // OK: local copy is modified
}

var r: real,
    A: [1..3] real;

foo(r, A);

writeln((r, A));   // writes (1.2, [3.4, 3.4, 3.4])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(inout x: real, inout y: [] real) {
  x = 1.2;   // OK: local copy is modified
  y = 3.4;   // OK: local copy is modified
}

var r: real,
    A: [1..3] real;

foo(r, A);

writeln((r, A));   // writes (1.2, [3.4, 3.4, 3.4])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(ref x: real, ref y: [] real) {
  x = 1.2;   // OK: actual is modified
  y = 3.4;   // OK: actual is modified
}

var r: real,
    A: [1..3] real;

foo(r, A);

writeln((r, A));   // writes (1.2, [3.4, 3.4, 3.4])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(ref x: real, ref y: [] real) {
  x = 1.2;   // OK: actual is modified
  y = 3.4;   // OK: actual is modified
}

const r: real,
      A: [1..3] real;

// foo(r, A);   // illegal, can't pass references to constants

writeln((r, A));   // writes (0.0, [0.0, 0.0, 0.0])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(const ref x: real, const ref y: [] real) {
  // x = 1.2;   // illegal: can't modify constant arguments
  // y = 3.4;   // illegal: can't modify constant arguments
}

const r: real,
      A: [1..3] real;

foo(r, A);   // OK to create constant references to constants

writeln((r, A));   // writes (0.0, [0.0, 0.0, 0.0])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(param x: real, type t) {
  …
  …
}

const r: real,
      A: [1..3] real;

// foo(r, A);   // illegal: can't pass vars and consts to params and types

writeln((r, A));   // writes (0.0, [0.0, 0.0, 0.0])
```

Argument Intents, by Example

- Arguments can optionally be given intents

```
proc foo(param x: real, type t) {
  …
  …
}

const r: real,
      A: [1..3] real;

foo(1.2, r.type);   // OK: passing a literal/param and a type

writeln((r, A));    // writes (0.0, [0.0, 0.0, 0.0])
```

5-body in Chapel: advance()

```
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: Alternative Using Iterators

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

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

Use of iterator

Definition of iterator

5-body in Chapel: advance() Using Iterators

```
proc advance(dt) {
  for (i,j) in triangle(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: Alternative Using References

```
proc advance(dt) {
  for (i,j) in triangle(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 Variables

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 general pointer: no way to point ‘ident’ to something else
  - 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
```

This is a Good Stopping Point for Now

Type Aliases and Casts

Type Aliases and Casts

- **Basic Syntax**

```
type-alias-declaration:
  type identifier = type-expr;

cast-expr:
  expr : type-expr
```

- **Description**
  - type aliases are simply symbolic names for types
  - casts are supported between any primitive types
- **Examples**

```
type elementType = complex(64);

5: int(8)    // store value as an int(8) rather than int
"54": int          // convert the string to an int
249: elementType  // convert the int to a complex(64)
```

Recall: Config Types

```
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
$ ./myProgram--start=2 --epsilon=0.00001
```

Enums

Enum Types

- **Somewhat like enum types in C:**

```
enum color {red, green, blue};   // can also be assigned values
```

  - Yet purer: don't coerce to integers, don't have default int values
  - Can also be printed!

```
var myColor = color.red;
writeln(myColor);                // prints 'red'
```

  - Support built-in iterators and queries:

```
for c in color do …
…color.size…
```

- **By default, must be fully-qualified to avoid conflicts:**

```
var myColor = red;               // error by default
```

  - But, may be 'use'd to avoid qualifying (like modules)

```
use color;                       // can use standard filters, renaming, etc.
var myColor = red;               // OK!
```

Modules and Use Statements

Modules

- **Syntax**

```
module-def:
  module identifier { code }

module-use:
  use module-identifier;
```

- **Description**
  - all Chapel code is stored in modules
  - `use`-ing a module makes its symbols visible in that scope
  - module-level statements are executed at program startup
    - typically used to initialize the module
  - for convenience, a file containing code outside of any module declaration creates a module with the file's name

Hello World in Chapel: Rapid Prototype

- **hello.chpl:**
  - rapid prototyping version:

```
writeln(”Hello, world!");
```

    - defines an implicit module “hello”
    - writeln() is its initialization

Program Entry Point: main()

- **Definition**
  - Chapel programs start by:
    - initializing all modules
    - executing main(), if it exists

M1.chpl:

```
use M2;
writeln("Initializing M1");
proc main() { writeln("Running M1"); }
```

M2.chpl:

```
module M2 {
  writeln("Initializing M2");
}
```

```
% chpl M1.chpl M2.chpl

% ./M1

Initializing M2
Initializing M1
Running M1
```

Hello World in Chapel: Production-Grade

- **hello.chpl:**
  - production-grade version:

```
module hello {
  proc main() {
    writeln(”Hello, world!");
  }
}
```

    - defines explicit hello module (with no module initialization code)
    - with explicit main() procedure

Module Deinitialization

- Modules also support deinit() routines to help clean up:

```
module hello {
  proc deinit() {
    writeln(”Goodbye, cruel world!");
  }
}
```

Use Statement: Basic Use

- Use statements make a module's symbols available

```
module myMod {
  var bar = true;

  proc myFunc() {
    use M;
    foo();

  }
}
```

```
module M {

 proc foo() { … }
}
```

Use Statement: Import Control

- **Use statements support import control**
  - 'except' keyword prevents unqualified access to symbols in list

```
use M except bar;  // All of M's symbols other than bar can be named directly
```

  - 'only' keyword limits unqualified access to symbols in list

```
use M only foo;    // Only M's foo can be named directly
```

  - Permits user to avoid importing unnecessary symbols
    - e.g., symbols which cause conflicts

```
module myMod {
  var bar = true;

  proc myFunc() {
    use M only foo;
    foo();
    var a = bar;   // Now finds myMod.bar, rather than M.bar
  }
}
```

```
module M {
 var bar = 13;
 proc foo() { … }
}
```

Use Statement: Symbol Renaming

- **Use'd symbols can also be renamed:**

```
use M only bar as barM;
```

  - Allows users to avoid…
    …naming conflicts between multiple used modules
    …shadowing outer variables with same name
    …while still making that symbol available for access

```
module myMod {
  var bar = true;

  proc myFunc() {
    use M only foo, bar as barM;
    foo();
    var a = bar;    // Still finds myMod.bar, rather than M.bar
    var b = barM;   // refers to M.bar
} }
```

```
module M {
 var bar = 13;
 proc foo() { … }
}
```

Use Statement: Fully Qualified References

- **Module symbols can also be fully qualified:**

  …M.bar…

  - Supports explicit naming—more verbose, but more precise

```
module myMod {
  var bar = true;

  proc myFunc() {
    use M only ;
    M.foo();
    var a = bar;     // Still finds myMod.bar, rather than M.bar
    var b = M.bar;   // refers to M.bar
} }
```

```
module M {
 var bar = 13;
 proc foo() { … }
}
```

Modules: Public/Private Declarations

- **All module-level symbols are (currently) public by default**

```
proc foo() { … }     // public, since not decorated
```

- **module-level symbols can be declared public/private:**

```
private var bar = …;
public proc baz() { … }
```

- **Can be used in declarations of:**
  - Modules
  - Variables, constants, and params
    - including configs
  - Procedures and iterators

More on Procedures, Iterators, and Methods

Procedure and Iterator Features

- pass by keyword / argument name

```
proc foo(name, age) { … }
foo(age=32, name="Tim");
```

- default argument values

```
proc foo(name, age=18) { … }
foo("Tim");
```

- formal type queries

```
proc foo(x: ?t, y: [?D] t) { … }
proc bar(x: int(?w)) { … }
```

- overloading
  - including where clauses to filter overloads

```
proc foo(x: int(?w), y: int(?w2)) where w == 2*w2 { … }
proc foo(x: int(?w), y: int(?w2)) { … }
proc foo(x, y) { … }
```

Methods

- **Methods are like procedures with an implicit 'this' argument**
  - Chapel supports both *primary methods:*

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

  - and *secondary methods*:

```
proc circle.circumference() {
  return 2*pi*radius;
}
var myCircle = new circle(radius=1.0);
writeln((myCircle.area(), myCircle.circumference());
```

  - Moreover, secondary methods can be defined for any type:

```
proc int.square() {
  return this**2;
}
writeln(5.square());    // prints 25
```

Method Overrides

- **Subclasses may override superclass methods**
  - but they must say so to avoid common error cases

```
class C {
  proc foo() { … }
  proc bar(x: int) { … }
  proc baz(x: int) { … }
  proc bax(x: int) { … }
}

class D: C {
  override proc foo() { … }
  override proc bar(x: int) { … }
  proc baz(x: real) { … }   // the differing type makes this is an overload
  proc bax(y: int) { … }    // the differing name makes this an overload
}
```

Method Overrides

- **Compiler checks override errors**
  - to avoid common error cases

```
class C {
  proc foo() { … }
  proc bar(x: int) { … }
  proc baz(x: int) { … }
  proc bax(x: int) { … }
}

class D: C {
  proc foo() { … }                          // error: overrides but fails to say so
  proc bar(x: int) { … }                    // error: overrides but fails to say so
  override proc baz(x: real) { … }          // error: no matching parent method
  override proc bax(y: int) { … }           // error: no matching parent method
}
```

Generics and Compile-Time Computation

Generic Procedures/Methods

Generic procedures can be defined using type and param arguments:

```
proc foo(type t, x: t) { … }
proc bar(param bitWidth, x: int(bitWidth)) { … }
```

Or by simply omitting an argument type (or type part):

```
proc goo(x, y) { … }
proc sort(A: []) { … }
```

Generic procedures are instantiated for each unique argument signature:

```
foo(int, 3);          // creates foo(x:int)
foo(string, "hi");    // creates foo(x:string)
goo(4, 2.2);          // creates goo(x:int, y:real)
```

Generic Objects

Generic objects can be defined using type and param fields:

```
record Table { param size: int; var data: size*int; }
record Matrix { type eltType; … }
```

Or by simply eliding a field type (or type part):

```
class Triple { var x, y, z; }
```

Generic objects are instantiated for each unique type signature:

```
// instantiates Table, storing data as a 10-tuple
var myT: Table(10);
// instantiates Triple as x:int, y:int, z:real
var my3: Triple(int, int, real) = new Triple(1, 2, 3.0);
```

Argument and Return Intents

- **Arguments can optionally be given intents**
  - (blank): varies with type; follows principle of least surprise
    - most types: `const in` or `const ref`
    - arrays, sync/single vars, atomics: `ref`
  - `in`: initializes formal using actual; permits formal to be modified
  - `out`: copies formal into actual at procedure return
  - `inout`: does both of the above
  - `ref`: formal is a reference back to the actual
  - `const` [`ref` | `in`]: disallows modification of the formal
  - `param`/`type`: actual must be a param/type
- **Return types can also have intents**
  - (blank)/`const`: cannot be modified (without copying into a variable)
  - `ref`: permits modification back at the callsite
  - `type`: returns a type (evaluted at compile-time)
  - `param`: returns a param value (evaluated at compile-time)

Ref return intents

- Procedures returning refs can be used in LHS contexts:

```
var A: [1..100] real;

proc getRandElt() ref {
  const randIdx = getRandIdx(A.domain);
  return A[randIdx];
}

getRandElt() = 4.2;
```

Compile-Time Computation

Type / Param Return Intents

- **Procedures can return types and params**
  - Results in evaluation of procedure at compile-time

```
proc getNTupleSize(param n: int, type eltType) param {
  return n*numBits(eltType);
}

proc getEltType(param useReal: bool, param size: int) type {
  if useReal then
    return real(size);
  else
    return imag(size);
}

param size = getNTupleSize(3, int(8));    // returns 24
var A: [1..100] getEltType(false, 32);    // an array of imag(32)
```

Folding conditionals

- Conditionals with ‘param’ expressions are folded

```
config param debug = false;
if debug then
  writeln("[debug] x is: ", x); // folded away unless debug == true
```

Unrolling Loops

- **Loops with param index variables are unrolled**
  - Currently only supported for ranges with param bounds:

```
for param i in 1..5 do
  if (i%2 == 0) then
    foo(i-1);
  else
    foo(2*i);
```

```
// equivalent to:
foo(2);
foo(1);
foo(6);
foo(3);
foo(10);
```

```
var tup = (1, 2.0, "three");

for e in tup do …e…                  // illegal since 'i' has no well-defined type

for i in 1..tup.size do
  const e = tup(i);                  // illegal since 'e' has no well-defined type

for param i in 1..tup.size do
  const e = tup(i);                  // legal since the loop is unrolled
```

User-generated compile-time messages

- **Permit user to generate errors/warnings at compile-time**
  - Messages printed if compiler resolves routine

```
proc foo(x: int(?w)) {
  if (w > 64) then
    compilerError("foo() called with an unusually large int");
  if (w == 8) then
    compilerWarning("foo() performs poorly for int(8) args");
  …
}
```

Special Subroutine Forms

Paren-less procedures

Procedures without arguments don't need parentheses

```
proc circle.diameter {
  return 2*radius;
}

writeln(c1.radius, " ", c1.diameter);
```

Supports time/space tradeoffs without code changes

- Store value with variable / field?
- Or compute on-the-fly with paren-less procedure / method?

Note: Like fields, such methods don't dispatch dynamically

Subroutine Calls vs. Array Accesses

- **Chapel doesn't distinguish between calls & array accesses**
  - An "array access" is simply a call to a special method named "this()'

```
class circle {
  proc this(x: int, y: real) {
    // do whatever we want here…
  }
}
myCircle[2, 4.2];   // calls myCircle.this()
```

  - Related: parens/square brackets can be used for either case:

```
A[i,j] or A(i,j)    // these are both accesses to array A / calls to A.these()
foo() or foo[]      // these are both calls to subroutine foo()
```

  - By convention, we tend to use [] for arrays and () for subroutine calls
    - but Fortran programmers may be happy to get to use () for arrays too…?
  - Like paren-less methods, view this as another time vs. space choice
    - can implement something as a subroutine or as an array
    - since Chapel's arrays are quite rich, access is not necessarily O(1) anyway

Default object iterators

- **Objects can have default iterators**

```
class circle {
  iter these() {
    // yield whatever we want…
  }
}
for items in myCircle do …   // invokes circle.these()
```

  - Similar to the 'this()' default accessor
  - Invoked using for-loops

```
for i in myCircle do …   // equivalent to for i in myCircle.these()
```

  - Overloads can support forall-based parallel / parallel zippered iteration
    - (true for any iterator)

Initializers for Records and Classes

Default Initializers

- Compiler provides default initializer for classes / records:

```
record R {
  var r: real;
  var i = 42;
}

var myR1 = new R(3.14);   // r=3.14, i=42
var myR2 = new R(i=33);   // r=0.0,  i=33
```

- Effectively equivalent to:

```
proc R.init(r: real = 0.0, i: int = 42) {
  this.r = r;
  this.i = i;
}
```

User-Defined Initializers

- **Users can also write their own initializers:**
  - Doing so overrides the default initializer

```
record R {
  var r: real;
  var i = 42;

  proc init() {
    this.r = genRandomNumber();
    // compiler fills in this.i = 42;
  }
}

var myR1 = new R(),          // r = <something random>, i = 42
    myR2 = new R(i=33);      // error!  No matching init() signature
```

Post-initializers

- **Users can also / alternatively write postinit() routines**
  - A hook that's invoked after object initialization

```
record R {
  var r: real;
  var i = 42;

  proc postinit() {
    writeln("Created an R!");
  }
}

var myR1 = new R(3.14);   // r=3.14, i=42 and prints "Created an R!"
```

  - Supports leveraging the default initializer with customization

Deinitializers

- **Records and classes also support deinitializers**
  - invoked when instance is freed

```
record R {
  var x, y, z: int;
  proc deinit() {
    writeln("R is going away now!");
  }
}

{
  var myR: R;
  …
}   // myR.deinit() will be called here, printing its message
```

Initializers and Class Hierarchies

- Initializers are a bit more interesting for class hierarchies

```
class C { var a: real; proc foo(…) { … } }
class D: C { var x, y, z: int; override proc foo(…) { … } }
class E: D { var …; override proc foo(…) { … }}

proc D.init() {
  writeln("In D's initializer");
  super.init(a=3.14);   // makes 'this' into a legal C object
  this.foo();           // calls C.foo()
  // compiler notes that x was skipped, inserts this.x = 0;
  this.y = 42;
  // compiler notes that z was skipped, inserts this.z = 0;
  this.complete();      // make 'this' into a legal D object
  this.foo();           // calls D.foo()
}

proc D.postinit() { this.foo(); }   // calls E.foo() for …new E(…)…
```

Initializers and Class Hierarchies

- For simplicity, the compiler can take care of many details

```
class C { var a: real; proc foo(…) { … } }
class D: C { var x, y, z: int; override proc foo(…) { … } }
class E: D { var …; override proc foo(…) { … }}

proc D.init() {
  // compiler notes there's no super.init(), so inserts it
  // compiler notes that x was skipped, inserts this.x = 0;
  this.y = 42;
  // compiler notes that z was skipped, inserts this.z = 0;
  // compiler notes there's no this.complete(), so inserts it
}

proc D.postinit() {
  // compiler notes there's no super.postinit(), so inserts it
  this.foo();
}
```

Class Instance Memory Management

Classes vs. Records

Classes

- **heap-allocated**
  - Variables point to objects
  - Objects could be anywhere
  - Support mem. mgmt. policies
- **‘reference' semantics**
  - compiler will only copy pointers
- **support inheritance**
- **support dynamic dispatch**
- **identity matters most**
- **similar to Java classes**

Records

- **allocated in-place**
  - Variables are the objects
  - Objects are “right here”
  - Always freed at end of scope
- **'value' semantics**
  - compiler may introduce copies
- **no inheritance**
- **no dynamic dispatch**
- **value matters most**
- **similar to C++ structs**
  - (sans pointers)

Memory Management Strategies Scorecard

Garbage Collection (like Java)	Manual 'delete's (like traditional C++)
+ safety guarantees + eliminates memory leaks + eliminates double-delete + eliminates use-after-free	– more errors possible – failure to delete results in leaks – double-delete possible – use-after-free possible
+ ease-of-use + no need to write 'delete'	– more burden on programmer – think about 'delete'
– implementation challenges due to distributed memory & parallelism	+ simpler implementation
– performance challenges – stop-the-world interrupts program – concurrent collectors add overhead – scalability may prove difficult	+ predictable, scalable performance

What about Rust?

- **Rust's approach prevents memory errors at compile time**
  - programs that might have a use-after-free result in compilation error
  - its *borrow checker* is the component raising these errors
- **Rust's approach also prevents race conditions**
  - since race conditions can introduce memory errors
- **Rust programmers can also opt out and write *unsafe* code**

Motivating Question

- **Can Chapel include something Rust-like?**
  - compile-time detection of use-after-free?
- **The Big Issue: Complete Checking and Race Conditions**
  - recall that a race condition can introduce a use-after-free error
  - For example:

```
proc test() {
  var myOwned = new Owned(new MyClass());
  var b = myOwned.borrow();
  cobegin with (ref myOwned) {
    { myOwned.clear(); }    // deletes instance
    { writeln(b); }         // races to use instance before delete
  }
}
```

Complete Checking and Race Conditions

- **Should Chapel rule out race conditions at compile time?**
- **A worthy goal, but the Rust strategy doesn't fit Chapel**
  - only one mutable reference to an object can exist at a time
  - if a mutable reference exists, no const references to that object
- **Such a strategy in Chapel would make these illegal:**

```
forall a in A { a = 1; }
forall i in 1..n { A[i] = i; }
forall i in 1..n { B[permutation(i)] = A[i]; }
```

- **Could a different strategy detect these race conditions?**
  - Maybe, but it would be difficult
  - Can the compiler prove that 'permutation' is a permutation?
  - If not, how would that be communicated to the compiler?

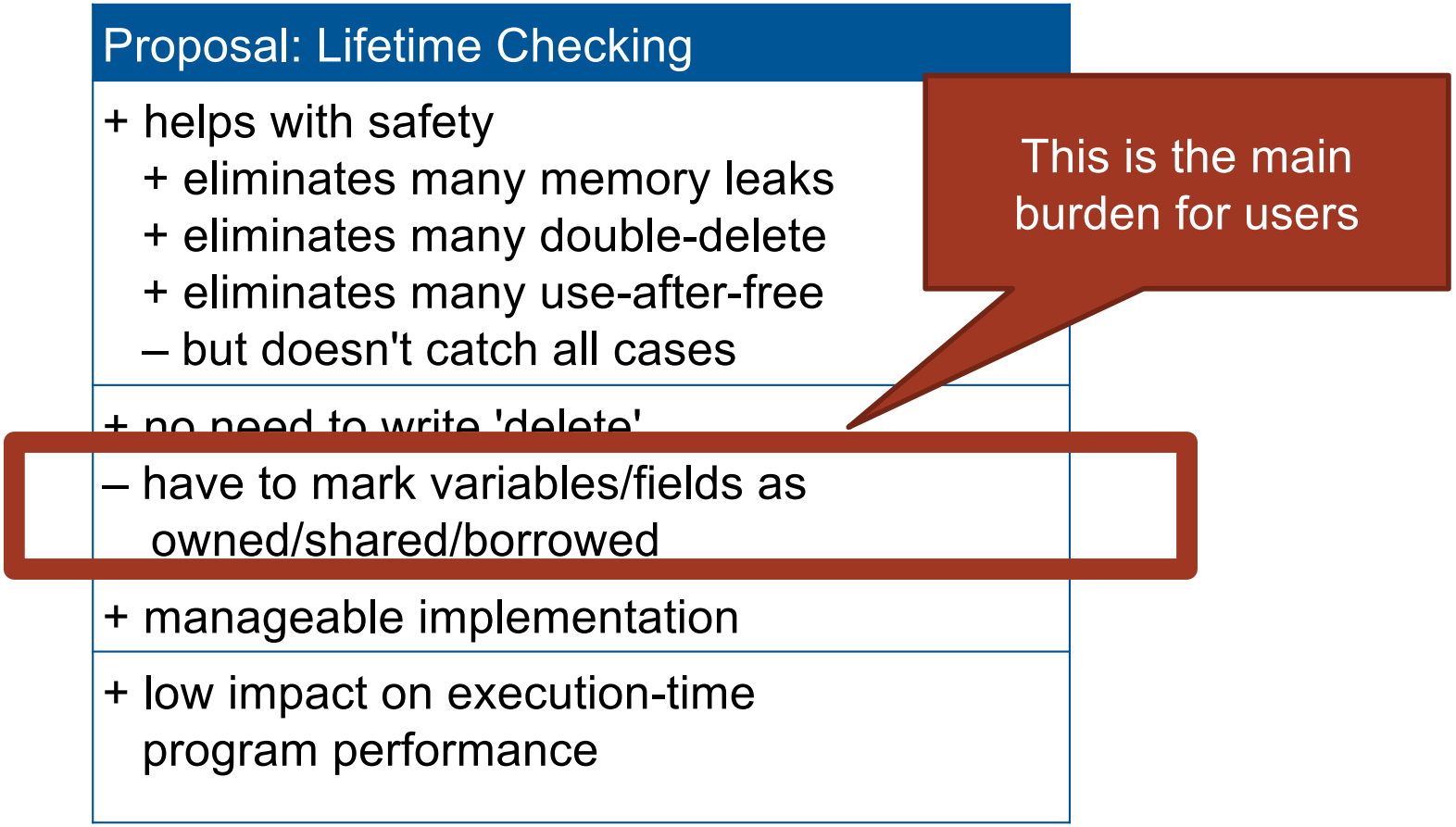
Chapel's Approach

- **Add incomplete compile-time checking to gain some of the benefits of garbage collection**

Proposal: Lifetime Checking
+ helps with safety + eliminates many memory leaks + eliminates many double-delete + eliminates many use-after-free – but doesn't catch all cases
+ no need to write 'delete' – have to mark variables/fields as owned/shared/borrowed
+ manageable implementation
+ low impact on execution-time program performance

General Goal

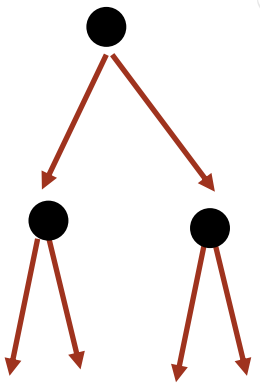
- **Add incomplete compile-time checking to gain some of the benefits of garbage collection**



Flavors of Class Instances

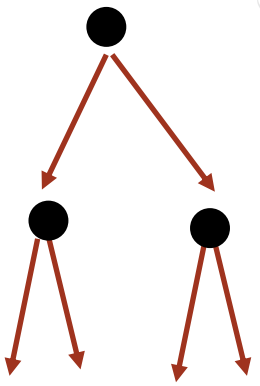
keyword	meaning
unmanaged	the instance is manually managed and needs to be deleted by the user
owned	the instance is auto-deleted at end of scope unless ownership is transferred
shared	the instance is reference counted
borrowed	the instance is managed elsewhere; this reference does not impact its lifetime

Mini Binary Trees: unmanaged version



```
class Tree {
  const left, right: unmanaged Tree;
}

proc Tree.init(const depth: int) {
  if depth >= 1 {
    this.left = new unmanaged Tree(depth-1);
    this.right = new unmanaged Tree(depth-1);
  }
}

proc Tree.deinit() {
  delete left, right; // T's subtrees must be explicitly deleted to avoid leaks
}

const T = new unmanaged Tree(2);
delete T;                    // T must be explicitly deleted or it will be leaked
```

Mini Binary Trees: shared version



```
class Tree {
  const left, right: shared Tree;
}

proc Tree.init(const depth: int) {
  if depth >= 1 {
    this.left = new shared Tree(depth-1);
    this.right = new shared Tree(depth-1);
  }
}


{
  const T = new shared Tree(2);
} // when T's scope ends, if nobody else points to it, it's deleted
  // and so are any of its subtrees that nobody else is pointing to
```

Shared and Sharing

- Multiple 'shared C' variables can point to the same instance
- Assigning or copy-initializing results in *sharing*

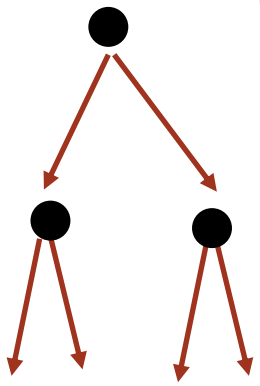
```
var otherShared = myShared;
// now otherShared and myShared point to the same instance
// the instance will be deleted when all references to the shared object go out of scope
```

- Default-intent 'shared' arguments also result in *sharing*
- 'shared' can be assigned 'nil' to release a reference

```
var x = new shared C();
x = nil;  // deletes the previous instance if no other shared variable refers to it
```

- Other methods are available, see '**shared**' docs

Mini Binary Trees: owned version



```
class Tree {
  const left, right: owned Tree;
}

proc Tree.init(const depth: int) {
  if depth >= 1 {
    this.left = new owned Tree(depth-1);
    this.right = new owned Tree(depth-1);
  }
}


{
  const T = new owned Tree(2);
} // when T's scope ends, if nobody else has taken ownership, it's deleted
  // and so are its subtrees
```

Owned and Ownership Transfer

- **Only one 'owned C' can point to a given instance**
  - thus, it can always destroy the instance when it goes out of scope
- **Assigning or copy-initializing results in *ownership transfer***
  - *ownership transfer* leaves the source variable storing 'nil'

```
var otherOwned = anotherOwned;
// anotherOwned now stores nil
```

- **'owned' can be assigned 'nil':**

```
var x = new owned C();
x = nil;  // deletes the previous value
```

- **Other methods are available, see '[owned]' docs**

Ownership Transfer on Argument Passing

- A default-intent 'owned' argument transfers ownership
- For example:

```
var global: owned C;
test();
proc test() {
  var x = new owned C();
  saveit(x); // leaves x 'nil' - instance transferred to arg & then to global
  // instance not destroyed here since x is 'nil'
}
proc saveit(arg: owned C) {
  global = arg; // OK — Transfers ownership from 'arg' to 'global'
  // now instance will be deleted at end of program
}
writeln(global);   // OK — Prints object allocated by test() as ‘x’
```

Borrowed and Borrowing

- **What is a borrow?**
  - a pointer to a class instance that does not impact its lifetime
- **Class types default to 'borrowed'**
  - 'C' is the same as 'borrowed C'
  - 'borrowed' is appropriate for the majority of class uses
- **The 'borrow' method is available to get a borrow**

```
var x = new owned C();
var b = x.borrow();
// .borrow() also available for shared, unmanaged, and borrowed objects
```

Coercions to Borrowed

- **Coercions to 'borrowed' keep code simpler:**

```
var x = new owned C();
compute(x); // Coerces to borrow to pass argument

proc compute(input: C) { ... }
// Could also be written as:
proc compute(input: borrowed C) { ... }
```

  - Coercions available from 'owned', 'shared', and 'unmanaged'
    - User can also cast these to the corresponding 'borrow' type

Borrowed Arguments Don't Impact Lifetime

- An argument with borrowed type does not impact lifetime
- For example:

```
var global: borrowed C;
test();
proc test() {
  var x = new owned C();
  saveit(x.borrow());
  // instance destroyed here
}
proc saveit(arg: borrowed C) {
  global = arg;  // Error! trying to store borrow from local 'x' into 'global'
  delete arg;    // Error! trying to delete a borrow
}
writeln(global);   // uh-oh! use-after free
```

Compile-Time Checking of Borrows

- **Lifetime checker is a new compiler component**
  - It checks that borrows do not outlive the relevant managed variable
- **For example, this will not compile:**

```
proc test() {
  var a: owned C = new owned C();
  // the instance referred to by a is deleted at end of scope
  var c: C = a.borrow();
  // c "borrows" the instance managed by a
  return c;  // lifetime checker error! returning borrow from local variable
  // a is deleted here
}

$ chpl ex.chpl
ex.chpl:1: In function 'test':
ex.chpl:6: error: Scoped variable c cannot be returned
ex.chpl:2: note: consider scope of a
```

Class Methods

- **Class methods borrow 'this'**

```
proc C.method() {
  writeln(this.type:string); // outputs the borrow type ‘C'
                             // a.k.a. 'borrowed C’
}
```

- **Coercions to borrow enable method calls on 'owned'**

```
var x = new owned C();
x.method(); // 'this' argument coerces to borrow in call
```

Class Subtyping

- **All class value kinds support subtyping**
  - Example shows 'owned', but 'shared', 'unmanaged', 'borrowed' all work

```
class ParentClass { ... }
class ChildClass: ParentClass { ... }

proc consumeParent(arg: owned ParentClass) { ... }
var x = new owned ChildClass();
consumeParent(x); // coerces 'owned ChildClass' to 'owned ParentClass'
                  // and consumes x, leaving it 'nil'

proc borrowParent(arg: ParentClass) { ... }
var y = new owned ChildClass();
borrowParent(y); // coerces 'owned ChildClass' to 'borrowed ParentClass'
                 // y still stores an object after this call
```

'new C' and 'new borrowed C'

- **What happens with an undecorated 'new'?**

```
var a = new C();
```

- **Here the type of 'a' is a 'borrowed C'**
  - the instance will be destroyed at the end the current block
    - think: “I’m borrowing this instance from this scope”
  - *ownership transfer* or *sharing* are not possible
  - returning 'a' results in a compilation error
- **The following are also equivalent to the above:**

```
var a: C = new owned C();     // coercing to borrow
var a = (new owned C()): C;   // casting to borrow
var a = (new owned C()).borrow();
```

Error-Handling

Error Handling: errors are classes

- Base 'Error' class is provided

```
class Error {
}
```

- 'Error' will typically be specialized

```
class MyStrError: Error {
  var msg: string;
}

class MyIntError: Error {
  var i: int;
}
```

Error Handling: throwing errors

- Throw errors with 'throw'

```
// throw a newly created error
throw new MyStrError("error message here");

// throwing an error stored in a variable
var e = new MyStrError("test error");
throw e;
```

- Mark procedures that can throw with 'throws'

```
proc mayThrowErrors() throws { ... }

proc mayThrowErrorsAlso(): int throws { ... }

proc mayNotThrowErrors() { ... }
```

Error Handling: try/catch

- **'try' and 'try!' are used to handle thrown errors**
  - { } blocks try to match to an associated 'catch' clause
  - Single statements will not match any 'catch' clauses

```
try {
  mayThrowErrors();
  mayNotThrowErrors();       // non-throwing calls may be included
  mayThrowErrorsAlso();
}
try! mayThrowErrors();       // halts on error
```

- **If an error is handled with no matching 'catch' clause:**
  - 'try' propagates the error
    - To an outer 'try', or out of the procedure (which must be marked 'throws')
  - 'try!' halts instead of propagating

Error Handling: try/catch

- **'catch' clause list matches against an 'Error' at run-time**
  - If a type filter matches the error, that block will be executed
  - Lack of a type filter means that all errors match

```
try {
  trickyOperation(badArg);
} catch err: IllegalArgumentError {  // IllegalArgumentError, subtypes
  writeln("illegal argument!");
} catch err: MyError {               // MyError, subtypes
  throw err;
} catch {                            // catch-all
  writeln("unknown error!");
}
```

Error Handling: ‘try’ expressions

- ‘try’/‘try!’ expressions are also available:

```
proc idiomOne() throws {
  var x = try intOrThrow(0); // throws errors upwards
  var y = try intOrThrow(1);
  return x + y;
}

proc idiomTwo() {
  return try! idiomOne(); // halts on error
}
```

Error Handling: Implicit modules

- **Implicit modules can call directly to throwing procedures**
  - program will halt if such subroutines throw
  - equivalent to wrapping all code in a try!
  - rationale: support quick sketching of code without handling every error

```
// implicitModule.chpl

thisCallMayThrow();    // equivalent to:  'try! thisCallMayThrow();'
```

Error Handling: Explicit modules

- **Explicit modules require handling / re-throwing errors**
  - rationale: now that this is a module, let's avoid surprises

```
module E {
  proc doesNotThrow() {
    // this potential error must be handled by a try! or a try with a catch all
    try! thisCallMayThrow();
  }

  proc doesThrow() throws {
    // OK because the procedure will throw errors upward
    thisCallMayThrow();
  }
}
```

Error Handling: Prototype modules

- ***Prototype* modules act like implicit modules**
  - A way to name a module without opting into handling all errors

```
prototype module NP {
  thisCallMayThrow();   // equivalent to:  'try! thisCallMayThrow();'
}
```

  - Future work: Link other behaviors to prototype modules?
    e.g., implicit / prototype module's symbols: public by default
    explicit module's symbols: private by default

Error-Handling and Parallelism

Error Handling: Parallelism, TaskErrors

- **'TaskErrors' aggregate errors across tasks**
  - 'Error' subtype that collects errors from tasks for centralized handling
  - Only thrown if there are one or more errors from the tasks
  - Can be iterated on, filtered for different kinds of errors

```
try {
  ...
} catch errors: TaskErrors {
  for e in errors {
    writeln("Caught task error e ", e.message());
  }
}
```

Error Handling: Parallelism, ‘cobegin’/‘coforall’

- ‘cobegin’ blocks and ‘coforall’/‘forall’ loops can throw
  - Errors will be stored in a ‘TaskErrors’, even if only one task is run

```
try {
  cobegin {
    canThrow(0);
    canThrow(1);
  }
} catch e: TaskErrors {
  ...
}
```

```
try {
  coforall i in 1..numTasks {
    canThrow(i);
  }
} catch e: TaskErrors {
  ...
}
```

Error Handling: Nested Parallelism

- **Nested loops or tasks do not produce nested 'TaskErrors'**
  - All errors are flattened to a single level

```
try {
  forall i in 1..m {
    forall j in 1..n {
      throw new DemoError();
    }
  }
} catch errors: TaskErrors {
  ...
}
```

Error Handling: Parallelism, 'begin'

- **Errors can be thrown from 'begin' statements as well**
  - Resulting errors can be caught from the surrounding 'sync' statement
    - Note: 'sync' statements are always considered to throw

```
try {
  sync {
    begin canThrow(0);
    begin canThrow(1);
  }
} catch errors: TaskErrors {
  ...
}
```

Defer Statements

Defer Statements

- **Support releasing general resources**
  - releasing locks, freeing memory/objects, closing files, etc.
- **Specifies a cleanup action for its enclosing block**
- **Cleanup actions run for *any* block exit**
  - through regular exit
  - subroutine return
  - error handling
  - ‘break’ and ‘continue’ within loops
- **Users could implement such patterns using records**
  - but that tends to require greater effort

Defer: Ugly Example Using Error-Handling

```
proc f(out releaseError: int) throws {
  var resource = allocateResource();
  var myInstance = new MyClass();
  if !setupResource(resource) {
    delete myInstance; // free resources if setup fails
    releaseError = releaseResource(resource);
    return;
  }
  try {
    throwingFunction();
  } catch e {
    delete myInstance; // free resources if we're throwing an error upwards
    releaseError = releaseResource(resource);
    throw e;
  }
  delete myInstance; // free resources upon normal return
  releaseError = releaseResource(resource);
}
```

Defer: Ugly Example Rewritten Using 'Defer'

```
proc f(out releaseError: int) throws {
  var resource = allocateResource();
  var myInstance = new MyClass();
  defer {
    // free resources regardless of which of the three ways we might return
    delete myInstance;
    releaseError = releaseResource(resource);
  }
  if !setupResource(resource) {
    return;
  }
  try throwingFunction();
}
```

Interoperation

Interoperation

- **Chapel supports calling between languages, primarily C**
  - …and by extension, languages that interoperate with C
    - e.g., Python and Fortran

- **Two modes:**
  - **extern**: Refer to symbols in other languages from Chapel
  - **export:** Call from other languages into Chapel subroutines
    - ultimately, would also expect to export symbols other than subroutines…

- **Chapel also supports a number of types for C interop**
  - c_char, c_int, c_string, c_size_t, c_void_ptr, c_ptr(<type>), etc.

Creating Extern Declarations

- **'extern' says that a symbol is defined outside of Chapel:**
  - tells Chapel what it needs to make use of the symbol:

```
extern type my_c_type_alias;
extern record my_c_struct {
  var x: c_int;
  var y: double;
}
extern proc sizeof(type t): size_t;
extern proc printf(format: c_string, args…);
```

  - symbols resolved by specifying C header files using 1 of 2 methods:
    1) source code: `require "c_header.h";`
    2) command-line: `$ chpl myChapelProg.chpl c_header.h`
  - supports "white lies" that the header file can resolve
    - e.g., my_c_struct has a field z that Chapel doesn't need to know about?
    - e.g., printf()'s format string is actually a const char* restrict

Two Tools for Generating Extern Declarations

1) **c2chapel:** standalone tool that converts C headers to Chapel

- https://chapel-lang.org/docs/tools/c2chapel/c2chapel.html
- Benefits: generates Chapel code that can then be edited
- Downsides: if header file evolves, needs to be re-run or re-edited

```
> c2chapel foo.h
```

C99

```
// foo.h
struct misc {
  char a;
  char* b;
  void* c;
  int* d;
};
```

Chapel

```
// Generated with c2chapel version 0.1.0

// Header given to c2chapel:
require "foo.h";

// Note: Generated with fake std headers
extern record misc {
  var a : c_char;
  var b : c_string;
  var c : c_void_ptr;
  var d : c_ptr(c_int);
}
```

Two Tools for Generating Extern Declarations

2) extern blocks: parses file-scope C code embedded in Chapel

- https://chapel-lang.org/docs/technotes/extern.html#support-for-extern-blocks
- Benefits: doesn't require a separate compilation / editing step
- Downsides: intermediate Chapel code not directly accessible to edit
  - Note: requires building Chapel with LLVM enabled due to reliance on clang

```
extern {
  int my_c_func(int x) {
    printf("C is printing this: %d\n", x);
    return x+1;
  }
  #include "gsl.h"
}
```

Creating Extern Declarations

- **'export' says a symbol may be used outside of Chapel:**
  - (it can also be called from within Chapel, of course)

```
export proc myParallelComputation() {
  var A = readDataInParallel("infile.txt");
  forall i in 1..n do
    A[i] = …
  return max reduce A;
}
```

  - current support is considered prototypical
    - compiler generates header files, Makefile stubs, Python / Cython files
    - argument types are limited to basic types, 1D arrays so far
    - see --library family of flags documented at:
      https://chapel-lang.org/docs/technotes/libraries.html
    - current status also documented in 1.18 release notes:
      - https://chapel-lang.org/releaseNotes/1.18/07-ongoing.pdf

What Else?

Other Base Language Features not covered here

- Varargs functions
- Unions

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