Language Improvements

Chapel Team, Cray Inc.
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Outline

- **Lexical Scoping Changes**
- **New Interpretation of Formal Array Arguments**
- **Type Methods and Iterators**
- **Public/Private Module-level Symbols**
- **Memory Consistency Model**
- **Other Language Changes**
Lexical Scoping Changes
Lexical Scoping: Background

- Variables used to be kept alive past their lexical scopes:

```chapel
{
    var A: [1..n] real;
    var count$: sync int;
    var x: real;
    begin with(ref x) { ...A... ...count$... ...x... }
    // ^^^ this task and its references to A, count$, and x could outlive their scope
} // So, traditionally, Chapel has kept these variables alive past their logical scope
```

- Consequences of this approach:
  - moves logical stack variables to the heap (like `x` and `count$` above)
  - incurs overhead for each access in original scope
  - incurs reference counting overhead
  - (or memory leaks in cases where we hadn’t yet added reference counting)
  - complicates the implementation
  - not particularly valued or leveraged by users
  - arguably surprising ("x still exists even though it left scope?")
Lexical Scoping: This Effort

- **Simplify language definition and implementation**
  - live references to variables leaving scope are now user errors:
    ```
    var flag$: sync bool;  // flag$ starts empty
    {
        var x: real;
        begin with(ref x) {  // create task referring to x
            flag$;  // block task until flag$ is full
            ...x...  // user error: access to x occurs after it leaves scope
        }  // end of task
        // x's scope closes
    }  // flag$ = true;  // fill flag$ only after x's scope closes
    ```
Lexical Scoping: Impact

**Impact:**

- Can now store logical stack variables on the stack
- Can improve and simplify the implementation
  - close some longstanding memory leaks
  - remove unnecessary reference counting
- Now freeing sync/single variables for the first time
  - This has been a longstanding source of memory leaks in the compiler
    - Previously, took very conservative “some task may be referring to it” approach
    - And never bothered to reference count…
Lexical Scoping: Status and Next Steps

Status:
- Other opportunities for leveraging new semantics still exist
- Program may crash if tasks refer to variables after they leave scope

Next Steps:
- Take further advantage of new semantics
  - stop heap-allocating variables in unnecessary cases
  - stop (or reduce) reference counting of arrays, domains, domain maps
  - close other leaks related to old semantics
- Implement runtime safety checks to guard against user errors
  - disable these checks for performance runs
New Interpretation of Formal Array Arguments
Array Formals: Background

- Domains in formal array types used to perform reindexing
  - rationale: permits functions to use most natural indexing scheme

\[
\begin{align*}
\text{var } & A: [1..n, 1..n] \text{ real; } & \text{// declare } n \times n \text{ array} \\
\text{factor}(A[lo..#b, lo..#b]); & \text{// pass } b \times b \text{ slice of } A \text{ into routine} \\
\text{proc } & \text{factor}(X: [1..b, 1..b] \text{ real) } \{ \text{ // reindex actual as } \{1..b, 1..b\} \\
& \text{...X[1,b]...} \text{ // } X[1,b] \text{ refers to } A[lo, lo+b-1]\}
\end{align*}
\]

- inspired by Fortran
Array Formals: Background

● In practice, this reindexing feature was rarely leveraged
  ● Most cases used formals to assert/document an actual arg’s domain:
    ```
    var A: [1..n] real;
    compute(A);
    proc compute(X: [1..n] real) …  // indicate expectation that actual is {1..n}
    ```

● For such “identical domain” cases, reindexing adds extra overhead
  ● our implementation of reindexing may be unnecessarily heavyweight
  ● yet, there will be cases in which it will never be free
    ● (e.g., reindexing may generate a distinct domain/array representation)

● In practice, performance-sensitive users fell back to workarounds:
  ```
  proc compute(X: [] real);  // give up on describing the domain
  proc compute(X: /*1..n*/ real);  // document domain with a comment
  ```
Given overheads and programmers’ intuition…

…interpret domains in formal arrays as constraints, not reindexing

specifically, “actual’s index set must match formal’s”

\[
\begin{align*}
\text{const} & \ DL = \{1..b, 1..b\}, & \quad & \text{\{1..b, 1..b\} domain} \\
& \ DD = DL \ \text{dmapped} \ \text{Cyclic}(...) & \quad & \text{\{1..b, 1..b\} domain}
\end{align*}
\]

\[
\begin{align*}
\text{var} & \quad AL: [DL] \ \text{real}, & \quad & \text{\{1..b, 1..b\} array} \\
& \quad AD: [DD] \ \text{real}, & \quad & \text{\{1..b, 1..b\} array} \\
& \quad AZ: [0..#b, 0..#b] \ \text{real}, & \quad & \text{\{0..b-1, 0..b-1\} array} \\
& \quad A: [1..n, 1..n] \ \text{real}; & \quad & \text{\{1..n, 1..n\} array}
\end{align*}
\]

\[
\begin{align*}
\text{proc} & \quad \text{factor}(X: [1..b, 1..b] \ \text{real}) & \quad & \text{\{1..b, 1..b\} array} \\
& \quad \text{factor}(AL); & \quad & \text{\{1..b, 1..b\} array} \\
& \quad \text{factor}(AD); & \quad & \text{\{1..b, 1..b\} array} \\
& \quad \text{factor}(AZ); & \quad & \text{\{1..b, 1..b\} array} \\
& \quad \text{factor}(A[1..b, 1..b]); & \quad & \text{\{1..b, 1..b\} array}
\end{align*}
\]
Array Formals: This Effort

- Given overheads and programmer intuition...
  - interpret domains in formal arrays as constraints, not reindexing
    - if formal has non-default domain map, actual’s domain map must be ==
      ```
      const DL = {1..b, 1..b}, // local {1..b, 1..b} domain
      DD = DL dmapped Cyclic(...); // distributed {1..b, 1..b} domain
      
      var AL: [DL] real,      // local {1..b, 1..b} array
      AD: [DD] real,          // distributed {1..b, 1..b} array
      AZ: [0..#b, 0..#b] real, // local {0..b-1, 0..b-1} array
      A: [1..n, 1..n] real;   // local {1..n, 1..n} array
      
      proc factor(X: [DD] real) ... // expect {1..b, 1..b} array distributed like DD
      factor(AL);                  // error: different domain maps
      factor(AD);                  // OK: index sets, domain maps ==
      factor(AZ);                  // error: different index sets
      factor(A[1..b, 1..b]);       // error: after slice, dom. maps differ
      ```
Array Formals: This Effort

- Given overheads and programmer intuition…
  - interpret domains in formal arrays as constraints, not reindexing
  - note that the actual and formal need not share a single domain/domain map

```plaintext
const DL = {1..b, 1..b},       // local {1..b, 1..b} domain
    DD = DL dmapped Cyclic(1);  // distributed {1..b, 1..b} domain

var AL: [DL] real,               // local {1..b, 1..b} array
    AD: [{1..b, 1..b} dmapped Cyclic(1)] real,  // dist. {1..b, 1..b} arr.
    AZ: [0..#b, 0..#b] real,           // local {0..b-1, 0..b-1} array
    A: [1..n, 1..n] real;              // local {1..n, 1..n} array

proc factor(X: [DD] real) …     // expect {1..b, 1..b} array distributed like DD
    factor(AL);                     // error: different domain maps
    factor(AD);                     // OK: index sets, domain maps ==
    factor(AZ);                     // error: different index sets
    factor(A[1..b, 1..b]);          // error: after slice, dom. maps differ
```

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Given overheads and programmer intuition...

...when reindexing is desired, user can insert at call-site manually:

```plaintext
var AZ: [0..#b, 0..#b] real;

proc factorL(X: [1..b, 1..b] real) ...
  // expect {1..b, 1..b} array
  factorL(AZ.reindex(1..b, 1..b));  // OK: after reindex, ind. sets equal
```

...ultimately support a sugar for “reindex to formal’s domain” case (?)

- Imagine something like:
  ```plaintext
  factorL(AZ.reindex(auto));
  factorL(=>AZ);
  (not that we’re particularly excited about either of these...)
  ```
Array Formals: Impact

- Programs that used array formals to assert size improved:

**Meteor Shootout Benchmark (n=2098)**

These versions were never rewritten to avoid domains in formal arguments

**N-body variations**

These versions were never rewritten to avoid domains in formal arguments
Array Formals: Impact

Programs relying on reindexing needed to be rewritten:
for example, in examples/benchmarks/hpcc/fft.chpl, the following:

```chapel
proc butterfly(wk1, wk2, wk3, X:[0..3]) {
    var x0 = X[0] + X[1],
    x1 = X[0] - X[1],
    ...  
}
```

became:

```chapel
proc butterfly(wk1, wk2, wk3, X: [?D]) {
    const i0 = D.low,
    i1 = i0 + D.stride,
    ...  
    var x0 = X[i0] + X[i1],
    x1 = X[i0] - X[i1],
    ...  
}
```
Array Formals: Impact

Programs relying on reindexing needed to be rewritten: for example, the following (naïve) dgemm-like routine:

```plaintext
proc dgemm (p: int, q: int, r: int,
            A: [1..p, 1..q] ?t,
            B: [1..q, 1..r] t,
            C: [1..p, q..r] t) {
    for i in 1..p do
        for j in 1..r do
            for k in 1..q do
                C[i,j] = A[i,k] * B[k,j];
}
```

became:

```plaintext
proc dgemm (A: [?AD] ?t, B: [?BD] t, C: [?CD] t) {
    for (ai,ci) in zip (AD.dim(1), CD.dim(1)) do
        for (bj,cj) in zip (BD.dim(2), CD.dim(2)) do
            for (ak,bk) in zip (AD.dim(2), BD.dim(1)) do
}
```
Array Formals: Status and Next Steps

Status:
● array formals are now, arguably, less surprising in Chapel
  ● though some power/convenience has also been removed
  ● though overheads have been removed for common “assert size” cases

Next Steps:
● design and implement a sugar for “reindex to match formal’s domain”
Type Methods and Iterators
Type Methods: Motivation

- **Chapel has only supported methods on variables/values**
  - for example:
    
    ```chapel
    class C {
        proc foo() { ... }
    }
    proc int.foo() { ... }
    var myC = new C();
    myC.foo(); 3.foo(); // OK to call methods on values/variables
    C.foo(); int.foo(); // errors: methods can only be called on values, not types
    ```

- **Users have long requested “static methods”**
  - goal: to call methods on types rather than just variables/values:
    
    ```chapel
    C.bar();
    int.bar();
    ```
Type Methods: This Effort

- This release adds support for defining methods on types:
  - for example:
    ```
    class C {
      proc type bar() { ... }
    }
    proc type int.bar() { ... }
    C.bar(); // OK to call type methods on matching types
    int.bar(); // OK to call type methods on matching types
    real.bar(); // error: no method named bar() defined on type ‘real’
    ```

- Syntactic approach:
  - like a ‘type’ constraint/intent on an argument…
    ```
    proc baz(type t) { ... } // baz()’s argument must be a type
    ```
  - …yet applied to the implicit ‘this’ argument
  - mirrors pre-existing ‘param’ and ‘ref’ intents for ‘this’ arguments
Type Methods: This Effort

● Note that, unlike C++ static methods, can’t call on values:

```plaintext
class C {
    proc type bar() { ... }
}
proc type int.bar() { ... }
var myC = new C();

myC.bar(); // error: can’t call type methods on values/variables
3.bar();   // error: can’t call type methods on values/variables
```

rationale:
- Consistent with ‘type’ intents in traditional Chapel argument contexts
- Removes convenience, not power (one can always call: `x.type.bar()`)  
- Avoids questions about whether dynamic dispatch applies
Type Methods: Status and Next Steps

**Status:** now implemented in compiler and available for use
- one bug filed against type methods on generic types

**Next Steps:**
- fix bug for type methods on generic types
- start using in our own standard module development as appropriate
Public/Private Module-level Symbols
Public/Private: Background

- All module level symbols were public
  - Internal modules used various approaches for “private” symbols
    - prefix identifiers with ‘_’ or ‘chpl_’
    - put symbols in submodules and use explicit module naming to access: ...
      PrivateSubModule.privateRoutine() ...
  - Neither of these are ideal solutions for namespace control

- Privacy controls are supported by most languages, e.g:
  - C++’s private, public, protected fields
  - Rust symbols are private by default, can specify as public
  - Python symbols can’t be explicitly named w/o import

- Chapel has always planned to provide better controls
  - Yet not considered a priority compared to parallelism, performance, ...
  - Until now – has become a FAQ as more libraries are written
Public/Private: This Effort

● public/private are now keywords
  ● Public remains the default
    ```
    private var foo = ...;
    public proc bar() { ... }
    proc baz() { ... }  // public, since not decorated
    ```

● Can be used in declarations of:
  ● Modules
  ● Vars, consts, and params
    ● including configs
  ● Procedures and iterators
Public/Private: Next Steps

● Greater control over module ‘use’ statements
  ● ‘only’ keyword to specify symbols to import
    ```
    use M1 only foo, bar;
    ```
  ● ‘except’ keyword to exclude symbols when importing
    ```
    use M1 except foo, bar;
    ```
  ● Add the ability to rename symbols when importing
    ```
    use M1 only foo as M1foo; // final syntax TBD
    ```

● Improve module ‘use’ transitivity
  ```
  module M { var x: int; }
  module M2 { use M; }
  ...use M2;...  // is ‘x’ visible here?
  ```
  ● Currently, the answer is always “yes”
  ● Ultimately, would like to support both transitive and non-transitive uses
    ● Challenges may exist, related to where generics are instantiated
  ● Plan to support this via public and private ‘use’ statements
Public/Private: Next Steps

- **Extend public/private to type definitions**
  ```javascript
  private type foo = ...;
  private enum bar = { ... };
  private class C { ... }
  private record R { ... }
  ```

- **Support public/private members of classes/records**
  - Determine inheritance story
    - Do we want/need an equivalent of ‘protected’?
    - Can a subclass of a ‘private’ class be ‘public’?
    - etc.
Memory Consistency Model
Memory Consistency Model: Background

● Motivation:
  Are you reasoning about code?
  You need a memory consistency model (MCM).
  ● MCM: rules to follow in order to get consistent, predictable results.

● Chapel has traditionally had an informal rule:
  Use sync/single vars to order memory operations.
  ● Didn’t cover atomic vars, program order with parallel constructs, etc.

● An informal model is not enough:
  Are you reasoning rigorously about code?
  You need a formal memory consistency model.
  ● Safer and more dependable than experience-based, ad-hoc coding
Memory Consistency Model: This Effort

- **Formalize and codify the Chapel MCM**
  - Work undertaken by MCM subteam

- **Gathered requirements, studied other memory models**

- **Produced new spec chapter: Memory Consistency Model**
Memory Consistency Model: Highlights

● Based on:
  *sequential consistency (SC) for data-race-free programs*
  
  … all Chapel tasks agree on the interleaving of memory operations and this interleaving results in an order consistent with the order of operations in the program source code.

  *Chapel Language Spec, v0.98*

● Derived from models for similar languages
  ● Reminiscent of C11, C++11, Java, UPC, Fortran 2008, …

● Describes effects of dynamic task creation, termination

● Plus: adds limited non-SC ordering
Memory Consistency Model: SC Ordering

- Operations on atomic/sync/single vars are ordered w.r.t. each other
  - All observers see the same order
  - Consistent with program order

- Operations on regular vars are not ordered w.r.t. each other
  - Except: within a task, same-address ops are seen in program order
  - Ops on regular vars are ordered w.r.t. ops on atomic/sync/single vars

- Task create/sync implies program order, thus mem order

- Data locality does not matter
Memory Consistency Model: Non-SC Ordering

- For improved performance in specific circumstances
- Relaxed atomics
  - Not ordered with respect to each other
  - Ordered only with respect to non-relaxed atomics and syncs/singles
  - Results guaranteed (it’s still atomic) and will be seen “eventually”
  - Example usage: parallel sum-reduction result variable
- Unordered operations on regular vars
  - Not ordered with respect to each other
    - Within a task, same-address operations may not be seen in program order
  - Ordered with respect to atomic operations
    - Not guaranteed to be seen until forced explicitly by atomic operation
  - Example usage: \( A[idx[i]] = \ldots \), where \( idx[] \) is a permutation
  - Neither syntax nor implementation done yet
Memory Consistency Model: Whither Now?

**Impact:**
- Less confusion about when memory operations are observable
- Less ad-hoc code to synchronize or communicate between tasks

**Status:**
- Conceptual model is complete and formalizes:
  - our intended (but informal) memory model
  - our implementation as it has existed for some time
- MCM chapter in spec is all-new and matches conceptual model

**Next Steps:**
- Improve spec for `memory_order` type constants and semantics
- Define syntax and semantics for unordered memory operations
- Research collaboration: Tatsuya Abe (Riken) plans to add Chapel to his MCM description language
Other Language Changes
Other Language Changes and Improvements

- Renamed ‘blank intent’ to ‘default intent’ for clarity
- Changed ‘use’ to ‘require’ for external dependences
  
  ```
  use "foo.h", "-lfoo";  ⇒  require "foo.h", "-lfoo";
  ```

- Added support for ‘continue’ statements in ‘param’ loops
- ‘select’ now only evaluates its expression once
- Added support for == and != on domain maps
  - Intuitively: “Do these map domains to the system in the same way?”
- Added support for hexadecimal floating point literals
  - (co-developed by Damian McGuckin, Pacific Eng. Systems Int’l)
- Added formfeed (‘\f’) to the set of whitespace characters
  - (co-developed by Damian McGuckin, Pacific Eng. Systems Int’l)
Interoperability Improvements

- Added support for renaming external records in Chapel
  - C struct declarations using typedefs...
    ```c
    typedef struct stat { ... } stat;
    ...
    
    // can use distinct names within Chapel if desired:
    extern "stat" record c_stat { ... }
    ```
  - This capability can also support structs that aren’t typedef’d in C:
    ```c
    typedef struct stat { ... };
    ...
    
    // as follows:
    extern "struct stat" record c_stat { ... }
    ```

- Added a ‘chplmalloc’ library permitting external code to call the Chapel allocator

- Stopped converting c_strings to strings when passed to generic arguments in external procedures
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