Language Improvements

Chapel Team, Cray Inc.
Chapel version 1.13
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Outline

● Core Language Improvements
  ● Improved Support for Strings
  ● Record Memory Management Improvements
  ● Use Statement Improvements (‘use’)
  ● Improving Reduce Intent Support
  ● Ref Return Intent Changes
  ● Passing Synchronization Variables to Generics
  ● Simple Synchronization Types Only

● Improvements to Built-in Routines
  ● Casting Types to Strings
  ● Improved min/max Type Signatures
  ● Comparison Operators on int/uint Pairs
  ● locale.numPUs()

● Other Language Improvements
Improved Support for Strings
Strings: Setting

Background:
● Since v1.11, we’ve been working on implementing strings as records
  …to remove special-case code from the compiler
  …to serve as a proxy for other interesting value types a user might write
  …as a means of closing string-based memory leaks
● Early drafts ran into problems in our implementation of records
  ● Imbalanced constructor/destructor calls, memory leaks, …
  ● Early record design/implementation was overly focused on POD cases
  ● Strings serve as an acid test for record semantics given their pervasive use
● Our string library has also historically been deficient

This Effort:
● Define a record-based string type
● Close string leaks
● Convert string literals to type string (were previously c_string)
● Support a modern set of library routines
Strings: Status

Status:

- Strings are significantly improved for version 1.13
  - now implemented as records
  - virtually leak-free, due to memory management fixes (see next section)
  - performance of strings has also improved
- Strings only support ASCII at present
  - want to support UTF-8 as well, and by default
Strings: Record-based Definition

- The string type currently looks like:

```chapel
record string {
    var len: int = 0; // length of the string, in bytes
    var size: int = 0; // size of buffer pointed to by buff
    var buff: c_ptr(uint(8)) = nil; // buffer to store the string
    var owned: bool = true; // deallocate buff on scope exit?
    var locale_id = chpl_nodeID; // locale where buff is allocated
}
```

- Implemented in Chapel modules, used by the compiler
  - Compiler hooks onto this type early in compilation
  - Alternative implementations could easily be swapped in

- Permitted us to remove special cases in the compiler
  - `string` is now handled like other records
    - modulo string-specific features like literals and param support
  - Removed coercions from `c_string` to `string`
Strings: literals ("text") now have type *string*

- **String literals were of type** *c_string*
  - Reason: lack of support for param records in the compiler
    - supporting param *c_strings* seemed more straightforward than *string*
  - Required implicit coercions to *string* in many cases
    ```chapel
    var x = "Hello, World";  // implicit runtime coercion from c_string to string
    ```
  - *c_string* isn’t a primary Chapel type, so this was unattractive

- **Made string literals be of type** *string*
  - *string* literals are now constructed at program startup
    - stored as locale-private global variables
  - Implicit coercions are no longer necessary
  - Introduced a new literal format for C strings (for interoperability only):
    ```chapel
    var my_c_string = c"Hello, World";
    ```

- **Added support for param strings**
  - Specific to *string*; general *param* records remain future work
Strings: Add new library routines

● Current string library routines:

```c
this()       // substring
these()      // iterate over chars
startsWith()
endsWith()
find()
rfind()
count()
replace()
split()
join()
strip()
partition()
localize()
c_str()
```

```c
isEmptyString()
isUpper()
isLower()
isSpace()
isAlpha()
isDigit()
isAlnum()
isPrintable()
isTitle()
toLower()
toUpper()
toTitle()
capitalize()
+
+=
*
==
!
<=
...```

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Strings: Impact

December 9th testing reflects the switch to string records:

- string-based memory leaks in our test suite went from 123MB to 22MB
  - by 1.13, reduced to < 1 KB

- # of tests with leaks in our suite was reduced by 2.6x

- fasta-lines version of fasta CLBG benchmark saw 2.7x speedup
  - another version improved 20%
Strings: Next steps

● Add proper Unicode strings
  ● Current plan: Support multiple string encodings
    ● focus on UTF-8 and ASCII only for now
    ● Will require changes to string library interfaces/implementation

● Performance and memory management improvements
  ● string representation
  ● string library algorithms
  ● general improvements for records

● Continue to refine string library based on user feedback
Record Memory Management Improvements
Record Memory Management: Background

- Chapel’s original design was overly naïve about records
  - Original design was overly focused on plain-old-data (POD) records
  - Yet, in practice, records can be used to manage heap-based data
    - e.g., string buffers, array elements, class objects, C pointers, …
  - Such cases revealed inadequacies in our approach
    - no user-facing copy constructors
    - failure to distinguish initialization from assignment
    - inconsistent invocation of destructors
    - inappropriate conversion of references to intermediate values
  - Consequences:
    - memory leaks, use of stale references, double-frees
    - sequences of unnecessary copy/free pairs
  - Have been working to course-correct, spurred on by string work
Record Memory Management: This Effort

- **Improve the implementation of records**
  - Eliminate errors when initializing, copying, destroying records
  - Ensure references to records are copied correctly
  - Lay foundation for extended constructor/destructor semantics

- **Chief catalyst: record-based strings**
  - Many other cases waiting in the wings as well:
    - arrays/domains (also special-cased today)
    - syncs/singles
    - barriers
    - GMP types
    - Random
    - ...
  - Building on records for these will
    - simplify the compiler
    - remove memory leaks
    - improve the user experience (e.g., no need to free barriers)
Record Memory Management: Possible Issues

- **Core issue:**
  - Failure to handle construction/assignment/destruction correctly

- **Overly aggressive autoCopy/autoDestory optimization**
  - These operations can be costly
  - Compiler uses memcpy() where it ought to be using assignment ops
  - Errors lead to leaks or the use of stale buffer handles

- **Creation of false aliases**
  - Wide references incorrectly converted to intermediate local values
  - Identity of original string is lost

- **Unnecessary, but valid, sequences of copy/destroy pairs**
  - \( b = \text{copy}(a); \text{destroy}(a); c = \text{copy}(b); \text{destroy}(b); \ldots \)
  - Commonly occur at function exits
  - Particularly evident after inlining
Record Memory Management: In Principle

- Using strings as motivation:

```plaintext
record string {
  var buff : c_ptr(uint(8)) = nil; // A class
  var owned : bool = true; // Enable shallow copy
  ...
}

proc foo(str0 : string) { // str0 defaults to const ref
  var str1 = "Hi"; // str1.buff initialized to a copy of "Hi"

  str1 = bar(str0); // assignment called; str1.buff reclaimed
  // str1 mem-copied from return temp

  return str1; // str1 returned to caller
}
```
Record Memory Management: In Practice*

● Using strings as motivation:

```plaintext
record string {
    var buff : c_ptr(uint(8)) = nil;        // A class
    var owned : bool = true;                // Enable shallow copy
    
}

proc foo(str0 : string) {                    // str0 defaults to const ref
    var str1 = "Hi";                         // str1.buff initialized to a copy of “Hi”
    var tmp0 : string = str0;               // str0 is de-referenced to a compiler temp

    str1 = bar(tmp0);                       // memcpy() called instead of assignment
    var ret0 = str1;                        // return temp inserted; ret0 a copy of str1
    return ret0;                           // ret0 returned to caller
}
```

(* while such errors did occur in practice, they typically wouldn’t for so simple an example)
Record Memory Management: Approach

- Compiler supports many record-like types
  - Records, tuples, ranges, iterators, arrays, ...
  - Chapel’s initial focus had been on parallelism and array performance
    - Tolerated leaks during early development — but no longer
    - Challenging to revise logic for strings without harming arrays

- Developed stress tests for records

- Initially, developed specialized code paths for string
  - Refactored logic for returning records by value
  - Tweaked logic for autoCopy/autoDestroy
  - Tweaked module code for String
  - Ensured new logic would extend to other record types

- Later, extended to general user-defined records
Record Memory Management: String Impacts

- Record-based strings integrated on Dec 8, 2015
  - No correctness regressions for pre-existing tests
    - Minor errors in some stress tests eliminated over subsequent 2 weeks
  - Resulted in significant memory leak improvements:

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
<th>Delta</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tests with leaks</td>
<td>2,798</td>
<td>1,064</td>
<td>-1,734</td>
<td>-62.0%</td>
</tr>
<tr>
<td>Bytes leaked (MiB)</td>
<td>1,081</td>
<td>981</td>
<td>-100</td>
<td>-9.2%</td>
</tr>
<tr>
<td>String copy data (MiB)</td>
<td>111</td>
<td>21</td>
<td>-90</td>
<td>-80.8%</td>
</tr>
<tr>
<td>String concat data (MiB)</td>
<td>10</td>
<td>0</td>
<td>-10</td>
<td>-100.0%</td>
</tr>
</tbody>
</table>

- String copy data reduced to 300 bytes by late Feb 2016
  - Result of several small changes
Record Memory Management: Status

- **New code paths apply to all user-defined records**
  - Strings no longer special-cased in this regard
  - Several other implementation-oriented records are still special-cased:
    - ranges, domains, arrays, distributions, tuples, iterators, …

- **Certain deficiencies remain**
  - Conversion of wide references to values can still occur
  - Extraneous sequences autoCopy/autoDestroy pairs remain
Record Memory Management: Next Steps

- Make implementation leak-free
- Remove other special cases
  - tuples, ranges, domains, arrays, …
- Rewrap existing types to leverage record improvements
  - sync/single, barrier, GMP, Random, …
- Finalize revised specification of record semantics
  - initializers (constructors) and destructors
  - record copies
  - returning records from functions
- Bring implementation in-line with specification
  - Implement user-facing features (e.g., initializers)
  - Eliminate unnecessary copies
  - Fix wide reference-to-record issue
Use Statement Improvements (‘use’)
Use Statement: Background

- Use statement brought in all visible symbols from module
- No way to selectively control which symbols were imported
  - Led to shadowing of outer-scoped variables with same name
  - Led to conflicts if two ‘use’d modules defined symbols with same name
  - Could fully qualify names to disambiguate, but fairly heavy-weight

```plaintext
module myMod {
  var bar = true;

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

```plaintext
module M {
  var bar = 13;
  proc foo() { ... }
}
```
Use Statement: Import Control

- Add import control for use statements
  - ‘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
    - Including 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
    }
}
```
Use Statement: Symbol Renaming

- Add ability to rename imported symbols
  
  ```
  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: Application to enums

● ‘use’ is now applicable to enums
  ● Frequently requested feature from users
    ● by default, unqualified access not supported to protect namespace
  ● Supports direct references to an enum’s symbols

```javascript
enum color {red, blue, yellow};
use color;
var foo = blue;  // instead of color.blue
```
Use Statement: Status and Next Steps

**Status:**
- All these features now available as of 1.13
- Cleaned up compiler representation of use statements

**Next Steps:**
- Support a means of requiring all accesses to be qualified
  - e.g., `use M except *; or use M only ;`
- Allow module-private use statements
  - Today’s uses are transitive
    - symbols used by another used module are transitoriely accessible
  - Anticipate challenges relative to point-of-instantiation for generics
- Warnings for uses that import…
  - …globals with types hidden by ‘only’ or ‘except’ lists
  - …functions that take arguments of hidden types
  - …functions with return types that import list hid
- Public/private type definitions and class/record members
Improving Reduce Intent Support
Reduce Intent Support: Background

- Reduce intents were introduced in 1.11

```cpp
var tmin, tmax, ttot: real;
forall i in 1..numTrials with (min reduce tmin,
max reduce tmax,
+ reduce ttot) {
    const start = getCurrentTime();
    // do some computation here
    const elapsed = getCurrentTime() - start;
    tmin = min(tmin, elapsed);
    tmax = max(tmax, elapsed);
    ttot += elapsed;
}
```

- They had some limitations:
  - only certain operators were supported:
    + * && || & | ^
  - could only be applied to forall-loops, not coforalls or cobegins

Create task-local copies of tmin, tmax, ttot. Reduce at task-end using min, max, +.
Reduce Intent Support: This Effort and Impact

**This Effort:** Added ability to use reduce intents with...

...min, max ops; simple user-defined reductions

```plaintext
var r: real;
forall a in A with (max reduce r) do
    r = max(r, a);
```

...coforall loops

```plaintext
var r: real;
coforall t in MyTasks with (+ reduce r) do
    r += t;
```

**Impact:** More opportunities to use reduce intents now

- can be more natural/efficient than reduce operators for many cases
- e.g., ISx benchmark
  - gathers timing statistics using min, max, + reduce intents on a single loop
  - more elegant and efficient
Reduce Intent Support: Next Steps

- Design and implement support for more complex cases:
  - expressing accumulation step in a general way
    ```java
    use ReductionLibrary;
    for all a in A with (myReduceOp reduce r) do
        r = ???(r,a);
    ```
  - one candidate:
    ```java
    r reduce= a;
    ```
  - element type differs from intermediate data and/or reduction result
    - e.g. min-k reduction
      - elements: real
      - intermediate data and result: k-tuple of reals
    - e.g. “is sorted” reduction
      - elements: real
      - result: bool “are all elements sorted?”
      - intermediate data: (something more complex than a real or bool)

- Reduce intents for cobegin statements

  How to express accumulation for a black-box reduction? Ideally, approach would be independent of reduction op
Ref Return Intent Changes
Ref Return: Background

Background:
● ‘ref’ return intent originally introduced to support array accessors
  ● used ‘var’ keyword at that point; ‘ref’ had not yet been introduced
● some accessors need to distinguish between reads and writes
  ● e.g., sparse arrays can be read anywhere, but only written at “non-zeroes”
● supported this via a compiler-provided ‘setter’ param
  ● cloned functions for setter vs. getter cases; chose clone based on callsite

```plaintext
proc mySparseArray.this(i: int) ref {
  if !explicitlyStored(i) {
    if setter then
      halt("trying to write to a non-zero location: ", i);
    else
      return 0;
  } else {
    return data[i];
  }
}
```
Ref Return: More Background

● **‘setter’ always felt like a wart in the language**
  ● clunky, invisible local param, provided only for ref-return functions

● **‘ref’ return intents resulted in unnecessary copies**
  ● counterintuitive
    ● “I said ‘return-by-ref’, why would a copy be made?”
  ● so why were they added?
    ● compiler cloned such functions to create getter vs. setter versions
    ● ‘getter’ versions always returned by value, so added copies
  ● user had no means to change this behavior
    ● i.e., no means to specify a different return intent for the getter function
  ● one result: excess copies/destroys for array accesses
    ● e.g., in one case, 4 layers of ‘ref’ calls resulted in 4 such copy/destroy pairs
    ● hurt performance for arrays of nontrivial types (e.g., strings, records)
Ref Return: This Effort

● Replaced ‘setter’ with a more principled approach:
  ● Support function overloads differentiated only by return intent
  ● call ‘ref’ return intent version in l-value contexts
    ● otherwise, call other version
  ● at first, may seem odd to resolve based on callsite…
    …yet this is what we were effectively doing for ‘setter’ already

● Added a new ‘const ref’ return intent
  ● Supports ‘ref’ vs. ‘const ref’ overloads for l-value vs. r-value contexts
  ● Or simply creating functions with ‘const ref’ return intent…

● For more information, see documentation:
  ● Language specification:
    See “Return Intents” (sections 13.7.1 – 13.7.3 in version 0.981 of spec)
  ● Language evolution page:
    http://chapel.cray.com/docs/1.13/language/evolution.html#ref-return-intent
Ref Return: Example

- Motivating example, revised:

```plaintext
proc mySparseArray.this(i: int) ref { // “setter” equivalent
  if !explicitlyStored(i) {
    halt("trying to write to non-zero location");
  } else
    return data[i];
}
proc mySparseArray.this(i: int) const ref { // “getter” equivalent
  if !explicitlyStored(i) {
    return 0;
  } else
    return data[i];
}

SpsArr[1] = 2.3; // writes call ref (black) version
writeln(SpsArr[1]); // reads call const ref (blue) version
```
Ref Return: Impact and Next Steps

Impact:
● removes the ‘setter’ wart from the language
● removes compiler clones of ‘ref’ return functions
● permits unnecessary copies to be avoided
● cases that used ‘setter’ must be rewritten as overloads
  ● yet, common case of ‘ref’ return without ‘setter’ case requires no changes
● avoids extraneous copies for array accesses, “getter” cases

Next Steps:
● Fix a bug in which the wrong overload is invoked for returned arrays
  ● ‘ref’ version is called in an r-value context
    ● harmless in many cases
    ● yet, in motivating example, would lead to an incorrect halt
  ● bug was only found recently, but almost certainly existed with ‘setter’ as well
Passing Synchronization Variables to Generics
Passing Syncs to Generics

Background:
● Passing syncs to generics “unwrapped” them in certain cases:

```plaintext
proc foo(const x) { writeln(isSync(x)); }
var s$: sync int = 42;
foo(s$); // acted like foo(s$.readFE()) and printed ‘false’
```
● Historically, believed that such unwrapping was natural & useful
● over time, this has seemed increasingly surprising

This Effort:
● Make generic sync arguments behave more like one would expect
● e.g., example above now behaves equivalently to:

```plaintext
proc foo(const x: sync int) { writeln(isSync(x)); }
var s$: sync int = 42;
foo(s$); // doesn’t unwrap ‘s$’ and prints ‘true’
```

Impact / Status:
● Synchronization variables are now far more principled than before
Simple Synchronization Types Only
Simple Sync Types Only

Background:

- Historically, Chapel permitted any type to be declared ‘sync’/’single’
  - This was thought to be attractively general and orthogonal — for example:
    - `var A$: [1..n] sync int; // an array of synchronized integers`
    - `var B$: sync [1..n] int; // a synchronized array of integers`
- Synchronized arrays could be interpreted sensibly in some cases:
  - `B$ = 0; // block until B$ is empty; zero; leave full`
- But others are less clear:
  - `B$[3] = 1; // how should the full/empty bit be involved?`
- Records, complexes have similar issues
- Some time ago, decided sync/single should support simple types only
  - effectively, ones with a single logical value
  - atomic variables already follow a similar philosophy
- Documented decision in the spec, but never enforced it in the compiler
Simple Sync Types Only

This Effort:
● Added enforcement to the compiler to restrict sync/single to:
  ● bools
  ● ints / uints
  ● reals / imgs
  ● strings
  ● classes
  ● since class variables are object references, they’re similarly “simple”

Impact/Status:
● Removes a dark semantic corner from the language / implementation
● Makes syncs/singles more like atomics

Next Steps:
● Consider adding support for atomic class variables
Simple Sync Types Only: Sidebar on sync void

Motivation:

● Some cases want full/empty semantics without an associated value

```go
var flag$: sync bool; // we often declare variables like this where we don’t
// care about the bool, just the full-empty state
```

● ‘sync void’ may be an appropriate type for such cases

Status:

● the ‘void’ type doesn’t work well in general
  ● have long-term plans to use it to optimize away variables / fields
    ```go
    var stride: if stridable then int else void;
    ```
  
● this effort does not explicitly prohibit ‘sync void’
  ● yet, like ‘void’, it doesn’t work well enough to be useful either

Next Steps:

● Complete implementation of ‘void’ type
● Make ‘sync void’ usable
Casting Types to Strings
Casting Types to Strings

**Background:**
- It's often useful to convert a type to a string
- In the past, has been done using a helper function, `typeToString()`:
  ```
  writeln("x's type is: ", typeToString(x.type));
  ```

**This Effort:**
- Belated insight: Why not support via casts from types to strings?
  ```
  writeln("x's type is: ", (x.type):string); // the parens are optional
  ```

**Impact/Status:**
- Unification of design; permits us to retire a lame helper function
- `typeToString()` still supported in 1.13 but gives a deprecation warning

**Next Steps:**
- Open question about whether varargs should support type/val mixes
  - This is why `writeln()` can’t simply accept types as arbitrary arguments today:
    ```
    writeln("x's type is: ", x.type);
    ```
Improved min/max Type Signatures
Improved min/max Type Signatures

Background:
- Traditionally, min and max have been defined completely generically:
  ```
  proc min(x, y) { return if (x < y) then x else y; }
  ```
- This causes problems for certain type signatures:
  ```
  min(myInt32, myUint32); // error: can’t resolve min’s return type
  ```
- Other operators support formal type arguments to avoid this:
  ```
  proc +(x: int(?w), y: int(w)) { ... } // and similarly for other types
  ```

This Effort:
- Declare ‘min’/’max’ signatures like other operators (and keep generics)

Status/Impact:
- ‘min’/’max’ now behave more uniformly with respect to other operators

Next Steps:
- Make ‘min’ / ‘max’ even more like other operators?
  ```
  smallest min= newValue;
  ```
Comparison Operators on int/uint Pairs
Comparison Ops on int/uint Pairs

Background:
- Chapel does not support operators on int / uint pairs by default
  ```chapel
  proc +(x: int, y: uint) { ... // throws a compile-time error }
  ```
- rationale: It’s ambiguous whether the result should be an int or a uint
  - It’s not hard to construct scenarios that would most naturally prefer either result
  - So, handle such cases via casting, user overloads, library-based overloads, or ...
- This rule was naively applied to comparison operators as well:
  ```chapel
  proc <(x: int, y: uint) { ... // throws a compile-time error }
  ```

This Effort:
- Realized that comparisons don’t have this problem, so added them
  - results are boolean
  - comparison can be computed despite differing value ranges
  ```chapel
  proc <(x: int, y: uint) {
    if x < 0 then return true;
    return (x:uint) < y;  // cast is safe due to previous conditional
  }  // in practice, this is implemented more concisely via short-circuiting operators
  ```
Comparison Ops on int/uint Pairs

Status / Impact:
- Integer comparisons are now much simpler to express without casts

Next Steps:
- Provide standard libraries of int/uint overloads for other operators
- Gives users the ability to select the semantics they want for a given scope
  - “int wins”
  - “uint wins”
  - “first argument wins”
  - …others?
locale.numPUs()
locale.numPUs() replaces numCores

**Background:** locale.numCores was inaccurate and insufficient

- actually returned number of hardware threads, not number of cores
- value always reflected OS limiting; physical count not available

**This Effort:** Provide a better interface

```python
proc numPUs(logical: bool=false, accessible: bool=true)
```

- resolves both issues: can return...
  ...cores or hardware threads (logical=false vs. true)
  ...accessible or physical (accessible=true vs. false)
- deprecate numCores

**Impact:** Provides a richer and more accurate interface

**Next Steps:** Improve accuracy of returned values

- certain OS accessibility patterns cause incorrect counts
Other Language Improvements
I/O Improvements

- deprecated Readers and Writers in favor of channels
- default I/O routines now ignore ‘param’ fields, like ‘type’
- channel.readbits/writebits accept additional integer types
- removed Chapel I/O support for *c_strings*
  - rationale:
    - led to problems across multi-locale settings
    - *c_string* intended for interoperability, not general Chapel operations
Other Language Improvements

- added support for subclassing generic classes
- added support for mixed int/uint range slicing
- added casting of fully-qualified enum strings to values  
  (contributed by Nick Park)  
  - e.g., the following now works: ...“color.red”:color...
- added support for comparing c_void_ptr to nil  
  (contributed by Nick Park)
- added support for implicitly coercing c_ptr to c_void_ptr
- added scalar versions of domain.exterior(), interior(), …
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