Language Improvements (Work-in-Progress)

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Work-in-Progress Features

- **Initializers**
  - Deinitializers
- **Error-handling**
- **User-Defined Reductions**

Initializers

Initializers: Background

- **Chapel's traditional constructor story was naïve**
  - Became increasingly clear as users/developers relied on OOP more
  - Lacked a good copy constructor / initializer story
  - Implementation generated multiple layers of copy operations

- **Have been developing 'initializers' as a replacement**
  - Consist of two phases:
    - phase 1: constrained initialization of fields
    - phase 2: general computation
  - Phases separated by call to one of:
    - super.init, for initialization of inherited fields (if any)
    - this.init, for common operations on the type (including field initialization)
  - Design being managed in CHIP 10
    - See also the 1.13 release notes on constructors
  - Constructors will be deprecated once initializers are complete

Initializers: Background

- **Last release: initial support for compliant initializers**
  - Supported initializer syntax
    - Included some Phase 1 semantic checks
  - Developed a strategy for generics and copy initializers
  - Further details in the [1.14 release notes]() on initializers

Initializers: Summary of this Effort

- Revised normalization logic for variable declarations
- Implemented initializers as ‘void’ methods
- Improved semantic checks
- Added support for copy initializers
- Started support for initializers on generic classes

Initializers: Background - Variable Declarations

- **Normalization breaks var decls into multiple AST nodes**
  - Resolution processes these nodes independently

  - Comparable declarations generated different AST and C code

```
var r1 : MyRecord = new MyRecord(10, 20);
var r2            = new MyRecord(10, 20);
```

  - But fundamentally both of these were treated as
    1. Default initialize r1/r2
    2. Custom initialize a compiler temp
    3. Copy/Assign the appropriate temp to r1/r2

  - Easy to optimize for primitive scalars but harder for record-like types

Initializers: This Effort - Variable Declarations

- **Refactored the implementation**
  - Includes early type analysis for a few simple cases
    - Initial focus on records with initializers
  - For a record, normalize generates AST to invoke an initializer
    - Function resolution selects the appropriate initializer
  - Simplifies business logic and AST in some cases
    - e.g. the following declarations generate consistent, simplified AST

```
var x : int;
var y = 10;
```

  - Reduces temps/copying for primitive scalars and records

Initializers: Background – Void Methods

- **1.14 implementation leveraged constructor infrastructure**
  - Provided a fast path for initial development, permitting us to…
    …experiment with the syntax
    …develop some initial tests

  - Constructors are effectively functions that return class/record values
    - Contributes to copying overhead since records are returned by copy-out

  - Constructors have special support within function resolution

Initializers: This Effort – Void Methods

- **Revised implementation relies on method infrastructure**
  - Initializers are methods with ‘void’ return type
  - No special support within function resolution for concrete types
  - Normalize gained semantic checks to enforce Phase 1 / Phase 2 rules
  - Methods receive a ‘ref’ argument to the object
    - No copying

Initializers: This Effort – Other Improvements

- **Errors are reported when**
  - .init calls or field initializations are present in loops
  - .init calls or field initializations are present in parallel code
  - any field initialization occurs prior to this.init()
  - a field is accessed before it is initialized in Phase 1
    - some exceptions to this persist
  - a const field is assigned in Phase 2

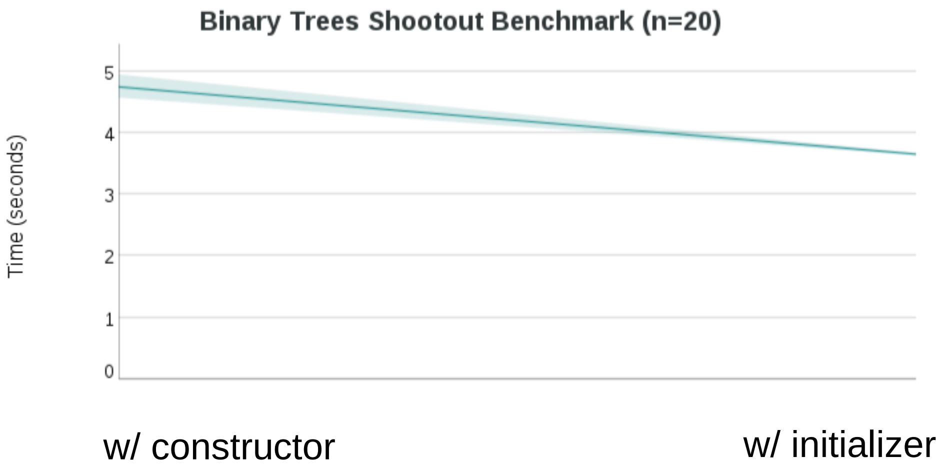
- **Conditional statements in Phase 1 now supported**
  - Initialization must be consistent across branches
  - If either branch includes a .init() call then both must do so
  - Compiler ensures omitted fields are initialized consistently

Initializers: This Effort – Generics

- **Support initializers for classes with generic fields**
  - type fields, param fields, vars/consts with neither types nor initializers
- **Appropriate initializer selected by function resolution**
- **Generic fields handled consistently with non-generics**
  - If initialization of a generic field is omitted in Phase 1…
    …if provided, the default field initializer is used
    …otherwise, an error is generated
  - Cannot update param or type fields in Phase 2
- **Instantiated / concrete type is known by end of Phase 1**
  - Creates new concrete type if necessary
    - Instantiates methods for the instantiated type

Initializers: Impact

- **Converted the Binary Trees shootout to use initializers**
  - Resulted in ~1.27x performance improvement
  - Resulted in cleaner generated code
    - Constructor code was 59 lines, 2 functions, set fields 3 times
      - Couldn’t write with explicit constructor due to a recursion bug
      - Relied on default constructor and special factory type method
    - Initializer code is 23 lines, 1 function, sets fields 2 times
      - Has a Phase 2 body. If implemented using Phase 1, would only set the fields once



Initializers: Status

- **Implementation has improved**
  - At the release of Chapel 1.14.0, had 46 passing tests and 25 futures
    - Passing tests tended to cover more basic features
    - Most futures captured important missing features
  - Today, have 131 passing tests and 40 futures
    - Passing tests growing in complexity
    - 31 of the futures are new (77.5%)

- **Simple tests work well**
  - Including most verification of initializer rules, simple generic classes
  - Some edge cases to fix

Initializers: Known Limitations

- **No support for conditional expressions:**

```
class Foo {
  const x: real;
  proc init(flag: bool) {
    x = if flag then 1.2 else 3.4;
  }
}
```

  - this case is now fixed on master

- **Fail to handle field initializers that include params**
  - Any initializer that omits initialization of the field 'v' will fail

```
class Foo {
  param p = 11;
  var   v = p + 4;
  …
}
```

Initializers: Known Limitations

- **Limited support for conditional statements**
  - Compiler may fail to apply phase 1 rules correctly along both branches
  - The following initializer should be accepted
    - A field is initialized before super.init() on then-branch
    - No field is initialized before this.init() on else-branch
    - Erroneous error claims that a field is initialized before a use of this.init()

```
class Foo {
  …
  proc init(a: bool) {
    if a then {
      x = 11; // proper field initialization prior to super.init() call
      super.init();
    } else {
      this.init(); // but this.init() in other branch causes issues
    }
  }
}
```

Initializers: Known Limitations

- **Copy-initializers vs. generic initializers**

```
record Foo {
  …
  proc init(arg) { // a generic initializer
    x = arg.someMethod(); // requires that arg implements someMethod()
  }
}
```

- Compiler may need the copy-initializer for Foo
- Compiler will instantiate this generic initializer as the copy-initializer
- Confusing error message if Foo does not implement **someMethod**()
  - May not be clear where compiler needs the copy-initializer

Initializers: Known Limitations

- **Incomplete support for generic types**
  - Compiler relies on body of the resolved initializer to construct type

```
var r1 = new MyGenericClass(10, 20.0);
```

  - Compiler fails to construct type when there is no initial value e.g.

```
var r2 : MyGenericClass(int, real);
```

- **Generic records not yet well-supported**

- **Other known limitations:**
  - Secondary initializers might be ignored in some cases
  - Poor error message when using field in argument list
  - No support for initializers for nested class/record
  - …(see futures)…

Initializers: Next Steps

- **For initializers on non-generic types:**
  - Implement missing features
    - Address current futures
    - Develop more tests
  - Improve validation for Phase 1 and Phase 2
  - Some general streamlining of AST within any method

- **For initializers on generic types:**
  - Support generic class variables with type specifications, e.g.:

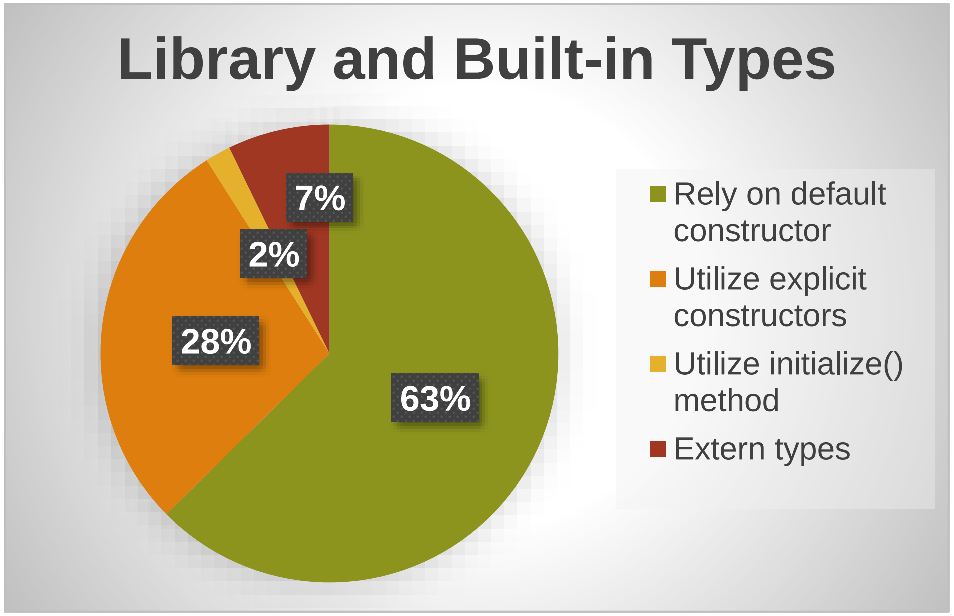
    ```
    var r1 : MyGenericClass(int, real);
    ```

  - Improve support for generic records

- **Determine whether objects should support ‘ref’ fields**
  - If so, add initializer support for them

Initializers: Next Steps

- **Update library and built-in types to use initializers**
  - See chart for break-down of the 222 library and built-in types
  - ~12 types with default constructors have special compiler support
    - will look into retiring that support
- **Generate default initializers and not default constructors**
- **Add support for noinit**
- **Convert constructor tests**
- **Deprecate constructors**



Initializers: Next Steps

- **Re-evaluate design decisions as we convert existing code**
  - Multiple syntax choices
    - e.g., distinguishing phases 1 and 2
  - What should the default phase be?
  - Could the distinction between phases be blurred in common cases?
    - e.g., support params / types in phase 2 since evaluated at compile-time?
  - Should ‘const’ fields be re-assignable in phase 2?
  - Generation of default initializers (currently squashed by user’s init())
    - Should user be able to opt-into retaining compiler’s default init()?
    - Does an initializer for a generic type constrain the possible types?
  - Importance of possible optimizations

Deinitializers

Deinitialization: Background

- **Deinitialization is the opposite of initialization**
  - actions to take when done with resources
    - e.g., release memory, close files
  - taken upon deleting a class, a record leaving its scope, etc.
    - implicitly includes deinitialization of class/record fields, array elements

- **Previously defined using '~typename' methods**

```
record MyRecord {
  ...
  proc ~MyRecord() { ... }
}
```

old-style naming

Deinitialization: This Effort

- **New name for deinitializers: ‘deinit’**

```
record MyRecord {
  ...
  proc deinit() { ... }
}
```

consistent with new terminology and initializer naming

  - if not specified by user, deinit() with empty body is added implicitly

- **Deinitialization and object fields:**

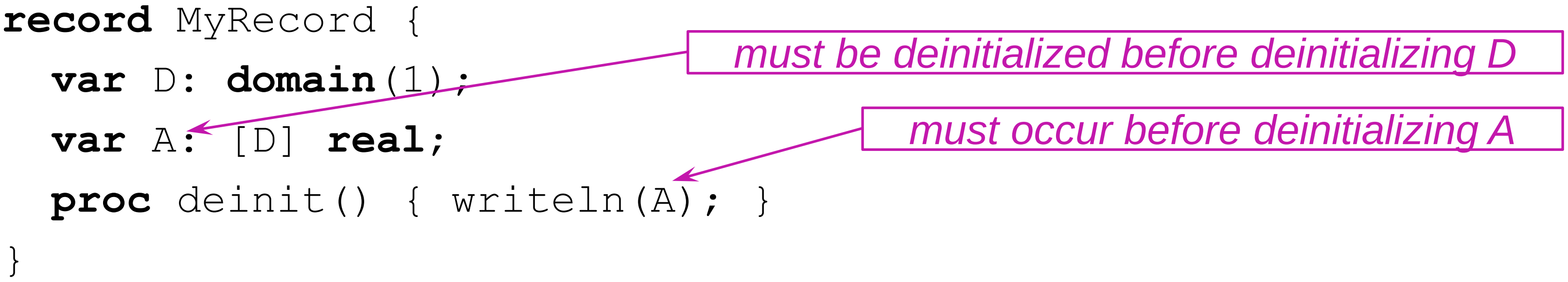
the main expected use case of deinit()

  - field type is a class ⇒ user must ‘delete’ it as appropriate
    - compiler does not add implicit ‘delete’
  - field type is a record ⇒ user cannot deinitialize it
    - deinitialized implicitly by compiler after executing deinit()

- **Introduced initial version of memory safety rules**

Deinitialization: Safety Rules – Overview

Motivation: prevent access to already-deinitialized fields



```
record MyRecord {
  var D: domain(1);
  var A: [D] real;
  proc deinit() { writeln(A); }
}
```

must be deinitialized before deinitializing D

must occur before deinitializing A

- akin to preventing access to not-yet-initialized fields at initialization
- also reduces risk of access to already-’delete’d class fields

Initial version: provides one way to achieve safety

- seeking user feedback
- initial rules are more restrictive
  - gives us room to relax if desired

Deinitialization: Safety Rules – Deinit Order

order of deinitialization actions:

```
  class Parent {
④ var field1...;
③ var field2...;
② proc deinit() {...}
  }
```

```
  class Child : Parent {
    var field3...;
① proc deinit() {...}
  }
```

before or after
2, 3, 4

- run deinit() in child class before deinit() in parent
- fields deinitialized after the deinit() for their class/record
  - in reverse declaration order
  - no user-visible effects for fields of primitive or class types

Deinitialization: Safety Rules – Restrictions

restrictions on deinit() methods:

- cannot invoke methods on ‘this’
- cannot pass ‘this’ as an argument to a procedure
- *can* access individual fields
  - including fields in superclass(es), if applicable

Deinitialization: Status and Next Steps

Status:

- both old and new naming can be used with 1.15
- ‘deinit’ name is used uniformly by Chapel code in repo
- memory safety rules: initial version is developed, partially implemented

Next Steps:

- refine the safety rules as necessary, complete their implementation
- improve error checking:
  - calling methods on ‘this’
  - passing ‘this’ to a function
- deprecate ‘~typename’ along with constructors

Error Handling

Error Handling: Background

- **Chapel had no language-level strategy for handling errors**
  - 'halt()' and "error" out arguments are used in practice, but insufficient
- **Language support was designed but unimplemented**
  - CHIP #8 proposed 'try', 'throws', 'throw', etc.
  - Design used Swift's error handling as a starting point

Error Handling: This Effort

- **Create a draft implementation of the design**
  - Draft offers basic functionality
  - Not yet integrated with tasks, 'on' statements
- **Seek feedback on design and implementation**
  - Encourage users to try the new error handling features

Error Handling: errors as classes

- **Base class 'Error' is provided**
  - For now, the initializer accepts a string argument

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

- **'Error' may be used directly, or as the root of a hierarchy**
  - Standard set of 'Error' subclasses not currently included

```
class MyError: Error {}

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

Error Handling: throwing errors

- Throw an error with 'throw'

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

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

- Mark procedures that can throw with 'throws'

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

proc mayThrowErrorsAlso(): A throws where { ... }

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
  - Single statement form relies on this behavior

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: default and strict mode

- **Two modes to support the tradeoff between…**

  …ensuring propagation of errors is clear (strict)
  …drafting code quickly (default)

- **Strict mode enforces visible control flow**
  - All calls to throwing procedures must be enclosed within 'try' / 'try!'
  - Otherwise, an error will be raised at compile-time

- **Default mode supports rapid prototyping**
  - Throwing calls need not be enclosed in 'try' / 'try!'
  - If the enclosing procedure is marked 'throws', propagate errors
  - Otherwise, halt on errors

- **Strict mode enabled with a compiler flag, --strict-errors**
  - Otherwise, compiler uses default mode
  - Expect to support more fine-grained approaches in the future
    - e.g., specify strictness per-module (or even per-function?)

Error Handling: limitations

- **Cannot span ‘begin’ / ‘cobegin’ / ‘coforall’ / ‘forall’ / ‘on’…**
  - No problems if error handling is kept entirely within the construct

```
begin {
  try {
    mayThrowErrors();
  } catch {
    writeln("handled internally");
  }
}
```

- **Halting errors do not yet print their type or message**
- **Virtual methods cannot yet throw**
- **Errors cannot yet be generic classes**

Error Handling: Status and Next Steps

Status:

- Basic implementation is in Chapel 1.15
  - Soliciting community feedback

Next Steps:

- Address the limitations on the previous slide
- Create a standard set of 'Error' classes
- Enable throwing errors from iterators
- Implement the 'defer' construct for state cleanup
- Design and implement a fine-grained strict mode
- Integrate error handling into the standard library
- Handle runtime errors by throwing Chapel errors

User-Defined Reduction Interface

Reduction Interface: Background

- **Chapel allows custom reduction operations…**

```
var myVar: real;
forall a in A with (MyReduceOp reduce myVar) do
  myVar reduce= a;
writeln(myVar);
```

… to be implemented using *reduction classes*

```
// today, a custom plus-reduction class might look like this
class MyReduceOp: ReduceScanOp {
  type eltType;                        // type of input
  var  value: eltType;                 // accumulation state
  proc identity return 0:eltType;
  proc accumulate(input) { value += input; }
  proc combine(childOp) { this.value += childOp.value; }
  ...
}
```

Reduction Interface: Background

- **Reduction class implements details of reduction**
  - for example:
    - identity value
    - how to *accumulate* an input value into the accumulation state
    - how to *combine* two accumulation states
  - they are invoked by compiler for reduce expressions and intents
  - the same interface is used for standard reductions (+, max, etc.)
- **Compiler works with reduction class to prevent data races**
  - compiler ensures no race when *accumulating* the input values
  - *combining* needs to lock the parent task's accumulation state

```
const parentOp = new MyReduceOp(...);
coforall task in 1..numTasks {
  const childOp = new MyReduceOp(...);
  ... accumulate input onto childOp ...
  parentOp.combine(childOp);
}
```

multiple child tasks may try to combine onto the same parent task at once

Reduction Interface: New Requirements

- **Separate accumulation state for reduce intents**

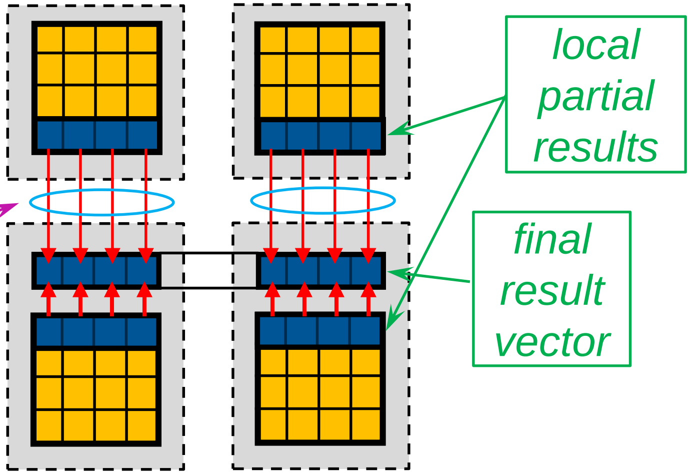
```
forall ... with (MyReduceOp reduce myVar) {
  myVar reduce= some input;
}
```

accumulation state to be accessible via shadow variable

- **Avoid lock state for partial reductions (w.i.p.)**

example: partial reduction of a Block-distributed matrix to a vector

for bulk communication of local results, want to have accumulation state without locks



- **Support synchronization strategies other than locking**
  - e.g., atomics

Reduction Interface: This Effort

Revisit the reduction interface in light of these requirements

- **Reduction class to be stateless**
  - instead, will provide methods to create accumulation state
- **Flexible synchronization strategy**
  - When accumulation state is created with argument parSafe=true
    - reduction class chooses/implements synchronization strategy
    - accumulation state includes lock/atomic/...
  - Otherwise, when parSafe=false
    - no need to include locks/atomics in accumulation state
    - this mode will be used for partial reductions

Reduction Interface: Impact

New interface definition

```
class MyReduceOp {         // no required parent class
  type inputType;          // distinct from the type of accumulation state

  // create accumulation state at top level
  // for reduce intents, seed it with value of user variable, otherwise with identity
  proc newGlobalAccState(initUserValue, param parSafe)  ...
  // create accumulation state in child task, initialized to identity
  proc newLocalAccState(ref parentState, param parSafe)   ...

  // accumulate and combine operations
  proc accumulate(ref parentState, ref localState, input) ...
  proc combine(ref parentState, ref localState)           ...

  ...
}
```

Reduction Interface: Impact

Example of compiler-generated calls to the interface

```
// a child task while performing a reduction
proc childTask(reduceClass, ref parentAS)
{
  // executed upon task startup
  var childAS = reduceClass.newLocalAccState(parentAS,
                                             parSafe=true);
  // generated for Chapel statement: userVar reduce= input;
  reduceClass.accumulate(parentAS, childAS, input);

  // if the child task has nested task constructs
  grandchildTask(reduceClass, childAS);

  // executed upon task tear-down
  reduceClass.combine(parentAS, childAS);
}
```

the reduction class instance

parent task's accumulation state

accumulation state to include lock/atomic/...

Reduction Interface: Status and Next Steps

Status:

- New interface design draft is available in issue #5470
- Compiler and Chapel code are still using the previous interface

Next Steps:

- Finalize the new interface
  - check that it works with partial reductions (w.i.p.)
- Implement the new interface
  - adjust the code base
  - fine-tune the interface based on experience
- Reduction record instead of reduction class?
  - well-scoped lifetime ⇒ avoid malloc/free

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