Improving Chapel and Array Memory Management

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Big Picture

- Chapel historically has leaked memory
- Made big progress over past several releases
  - for 1.13, significantly improved strings
  - for 1.15, significantly improved arrays
- Chapel 1.15 is pretty good!
Improvements in leaks

Number of tests that leak

Gigabytes leaked in tests

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Leaks were always there
Fixing leaks required significant effort
Rest of the Talk

- What was going wrong with array memory management?
- How did we fix it?
- A challenge we discovered along the way
- Performance Impact
What was going wrong with arrays?
What was going wrong with arrays?

- **Array memory management used reference counting**
  - to enable original language semantics

- **Largest source of memory leaks in Chapel 1.14**
  - distributed arrays accounted for most leaked data

- **Implementation overheads hurt performance**
  - Benchmarks spent significant time handling array reference counting
    -Supported a ‘noRefCount’ setting to measure/reduce impact
    -Sometimes helped dramatically, but guaranteed arrays would be leaked

- Array memory management overheads could be surprising:
  ```
  var size = A.domain.size; // changed reference counts!
  ```
Where did the leaks come from?
Where did the leaks come from?

- Array memory management strategy had two goals:
  1. Keep arrays alive past lexical scope
     - when an array slice/view outlives the original array
     - when arrays are used in ‘begin’ statements
  2. Minimize array copies

- But…
  - Implementation erred on keeping arrays alive to the point of leaking
  - Reference counting approach was expensive and overly conservative
  - Language definition did not clearly specify array return behavior
How did we fix it?
How did we fix it?

- **Removed array reference counting**
  - no longer necessary

- **Adjusted language to simplify the task**
  - arrays return by value by default
  - arrays no longer outlive lexical scope

... and worked hard on the implementation ...
Returning Arrays
Returning Arrays

- Arrays have historically returned by 'ref' by default
  - this design interfered with array memory management improvements

- In 1.15 they return by value by default
  - to make them more similar to records
  - to simplify the language and its implementation

```plaintext
var A: [1..4] int;
proc f() {
    return A;  // new in 1.15: return by value
}
ref B = f();
B = 1;
writeln(A);
// printed 1 1 1 1 historically
// prints 0 0 0 0 after this work
```
Returning Arrays

- When old behavior is desired, use 'ref' return intent
  - should result in behavior that’s backwards-compatible with 1.14

```pascal
var A: [1..4] int;
proc f() ref {  // explicit ref return
  return A;
}
ref B = f();
B = 1;
writeln(A);
// prints 1 1 1 1
```
Scoping
Arrays are now destroyed when they go out of scope
- ‘begin’ statements and array slices no longer affect array lifetime

```plaintext
proc badBegin() {
    var A: [1..10000] int;
    begin {
        A += 1;
    }

    // User error: A destroyed here at function end, but the begin could still be using it!
}
```

Builds upon earlier work
- 1.12 no longer extends lifetime for general variables used in 'begin'
- 1.15 first to rely on this property for arrays
A surprise along the way
A surprise along the way

We notice a language problem while studying the performance impact of array changes on miniMD

Key background:

1. Historically, default argument intent for arrays was 'ref'
   ● designed as a convenience for programmers
   ● avoids surprising programmers used to modifying array formal

2. Sparse arrays use return intent overloads
   ● to have different behavior on element read and write
   ● writing “zero” values of a sparse array is an error
   ● reading the “zero” values of a sparse array is fine
Consider this example with a sparse array of int:

```plaintext
var dense = {1..10};
var sps: sparse subdomain(dense); // domain is initially empty

var A: [sps] int; // sparse array of integers, only storing "zero" value

writeln(A[3]); // outputs 0, the "zero" value
```
What about a sparse array of arrays?

```plaintext
var dense = {1..10};
var sps: sparse subdomain(dense);

var A: [sps] [1..5] int; // sparse array of arrays

writeln(A[3]);
```
Unintended Consequences

• What about a sparse array of arrays?

```javascript
var dense = {1..10};
var sps: sparse subdomain(dense);

var A: [sps] [1..5] int;

writeln(A[3]); // surprising: halts

// attempting to assign a 'zero' value in a sparse array: (3)
```
Unintended Consequences

● What about a sparse array of arrays?
  ```
  var dense = {1..10};
  var sps: sparse subdomain(dense);

  var A: [sps] [1..5] int;

  writeln(A[3]); // surprising: halts
  // attempting to assign a 'zero' value in a sparse array: (3)
  ```

● What's happening in this example?
  ● writeln() takes its arguments by default intent
  ● default intent for an array is 'ref'
  ➔ writeln() appears to the array implementation to set its argument
  ● setting a sparse array’s “zero” values via indexing is not permitted
● Changed the default intent for arrays...
  ...to 'ref' if the formal argument is modified in the function body
  ...to 'const ref' if not

```plaintext
proc setElementOne(x) {
  // x is modified, so x has 'ref' intent
  x[1] = 1;
}

var A:[1..10] int;
setElementOne(A);

proc getElementOne(y) {
  // y is not modified,
  // so y has 'const ref' intent
  var tmp = y[1];
}

var B:[1..10] int;
getElementOne(B);
```
Fixing It

● Motivating cases now work as you’d expect:

```plaintext
var dense = {1..10};
var sps: sparse subdomain(dense);

var A: [sps] [1..5] int;

```

● Why does this now work?

  ● writeln() still takes its arguments by default intent
  ● because it only reads its args, the default intent for arrays is ’const ref’
  → writeln now calls the array’s read accessor
  ● reading a sparse array’s “zero” values is fine
Performance Impact
Reworking Array Memory Management

- Substantial single-locale performance improvements
  - up to 7x speedup in some cases
Reworking Array Memory Management

- Some big multi-locale performance improvements
  - up to 6x speedup
Adjusting Array Intent

- Led to about 4x speedup for miniMD on 16 nodes
  - StencilDist uses return-intent overloads to return from a cache
  - This effort enabled the cache for arrays-of-array stencils, as in MiniMD
Questions?

- No More Array Reference Counting!
- Arrays Return by Value
- Tuples Capture Arrays by Reference
- Array Intent
Building upon Record Memory Management

- Arrays, strings use a record to manage memory
- But records had memory management issues
- Fixing those has enabled progress
Tuples

- Details of tuple behavior have never been well-defined
  - things have worked “well enough” for this not to receive more attention

- Array memory fixes ran afoul of issues with tuples

- For example:
  ```
  proc f( tupleArg ) {
    return tupleArg;
  }
  var A, B: [1..n] int;
  f( (A, B) );
  ```
  - are A and B passed by value or by reference into f?
  - does returning tupleArg return the contained arrays by value or by ref?
Tuples

- Reworked the tuple implementation to support array fixes
  - guiding principle: 1-element tuples behave similarly to plain elements
  - implementation is now more direct and straightforward

- Returning to the example:
  ```
  proc f( tupleArg ) {
    return tupleArg;
  }
  var A, B: [1..n] int;
  f( (A, B) );
  ```

  - are A and B passed by value or by reference into f?
    - by reference, because arrays pass by 'ref' / 'const ref' by default
  - does returning tupleArg return the contained arrays by value or by ref?
    - by value, because arrays return by value by default
Language Changes

- For more information, see
  - CHIP 13: *When Do Record and Array Copies Occur?*
  - CHIP 6: *Tuple Semantics*
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