Improving Chapel and Array Memory Management

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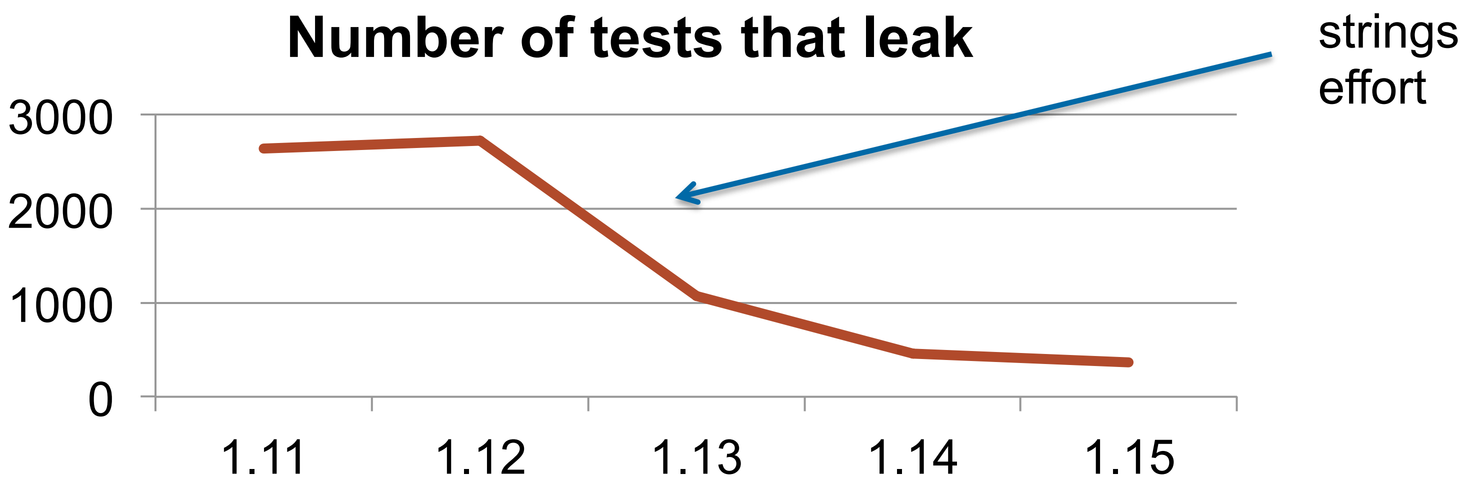
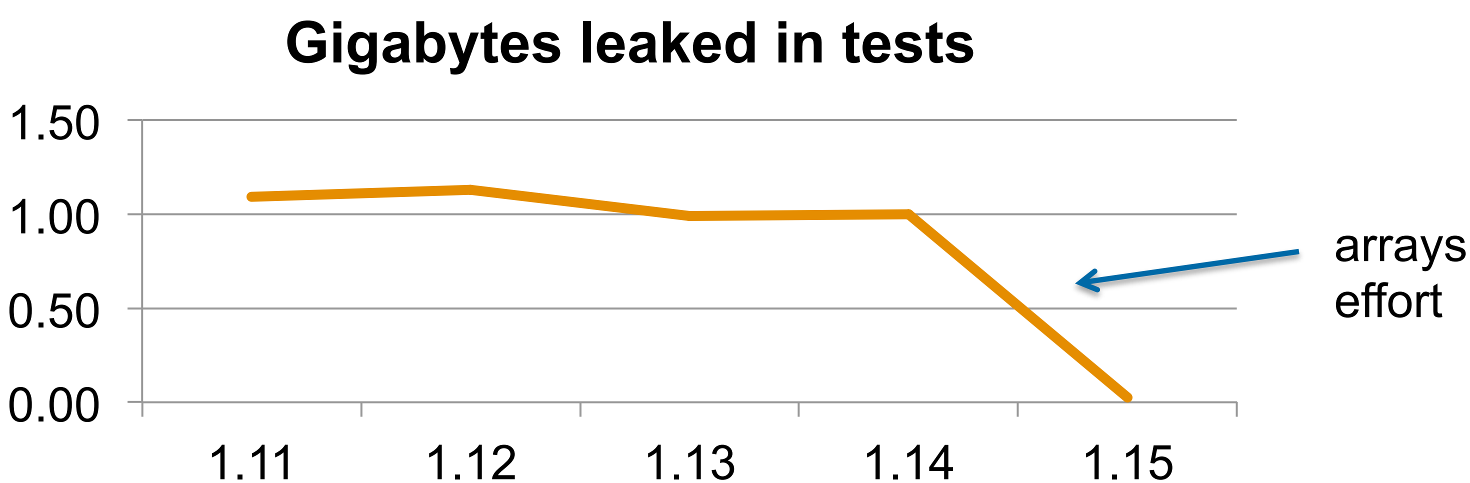
Big Picture

- **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





Leaks were always there

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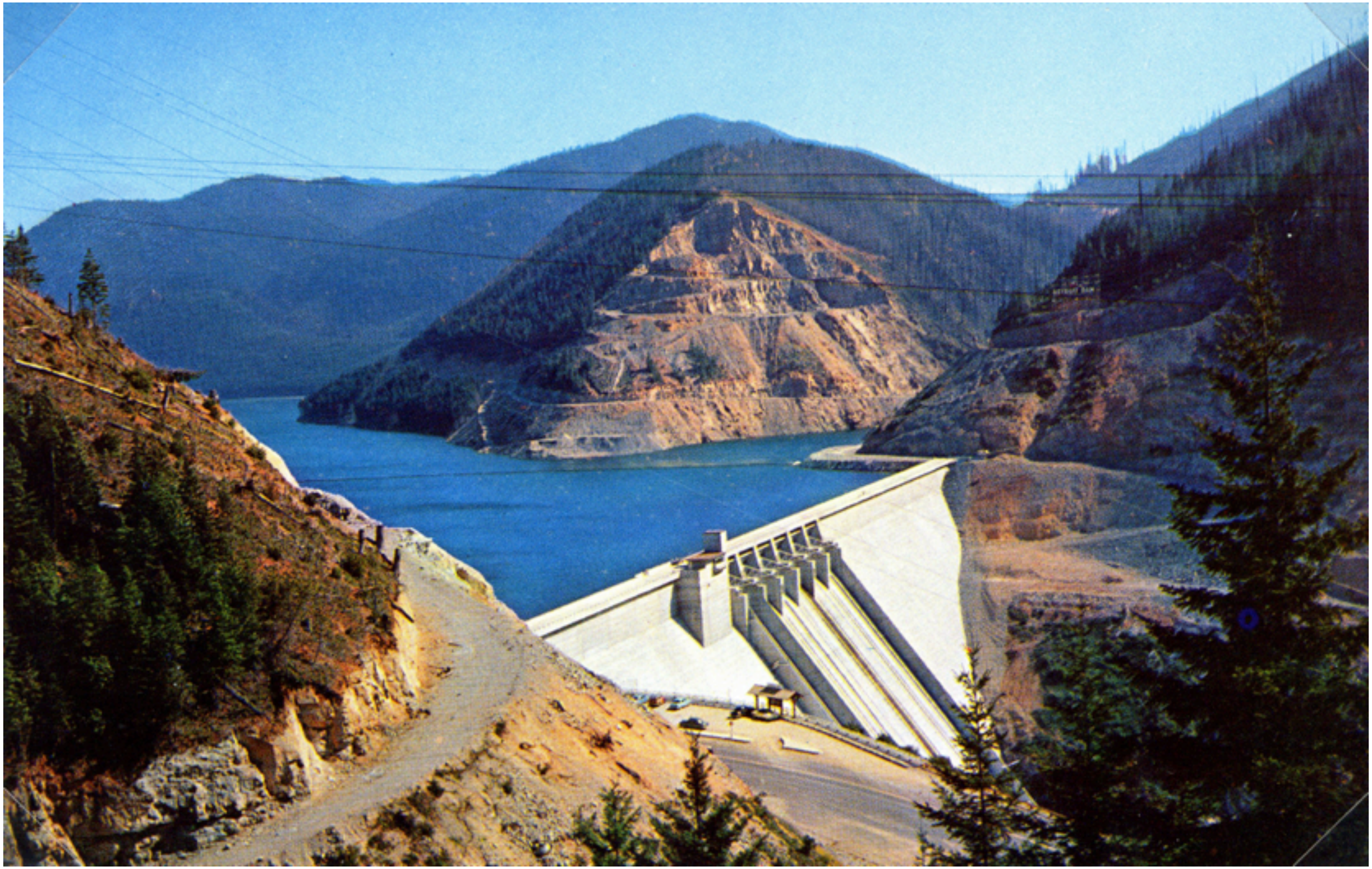
Fixing leaks required significant effort



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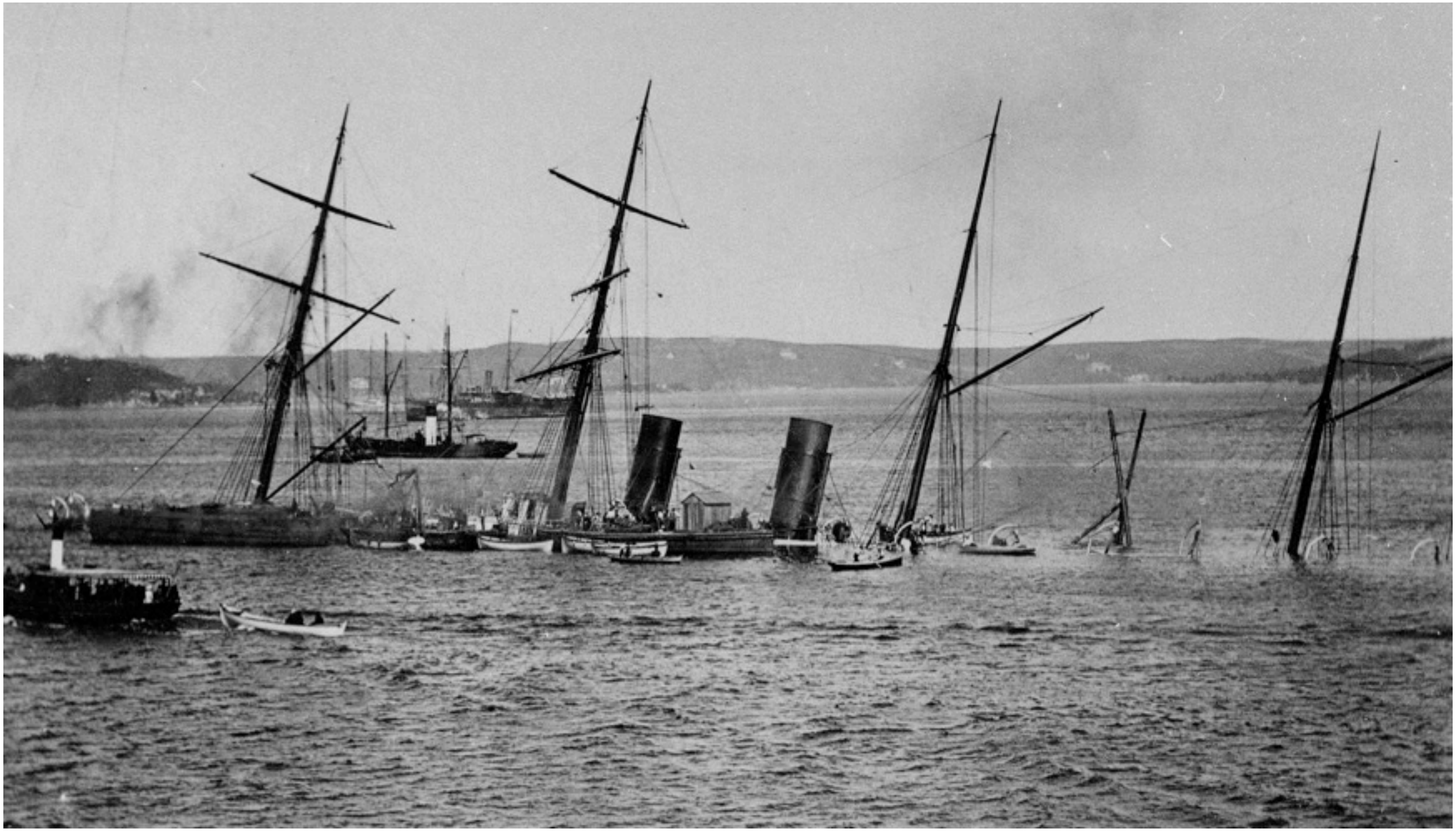
Rest of the Talk

- 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?



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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?

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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?

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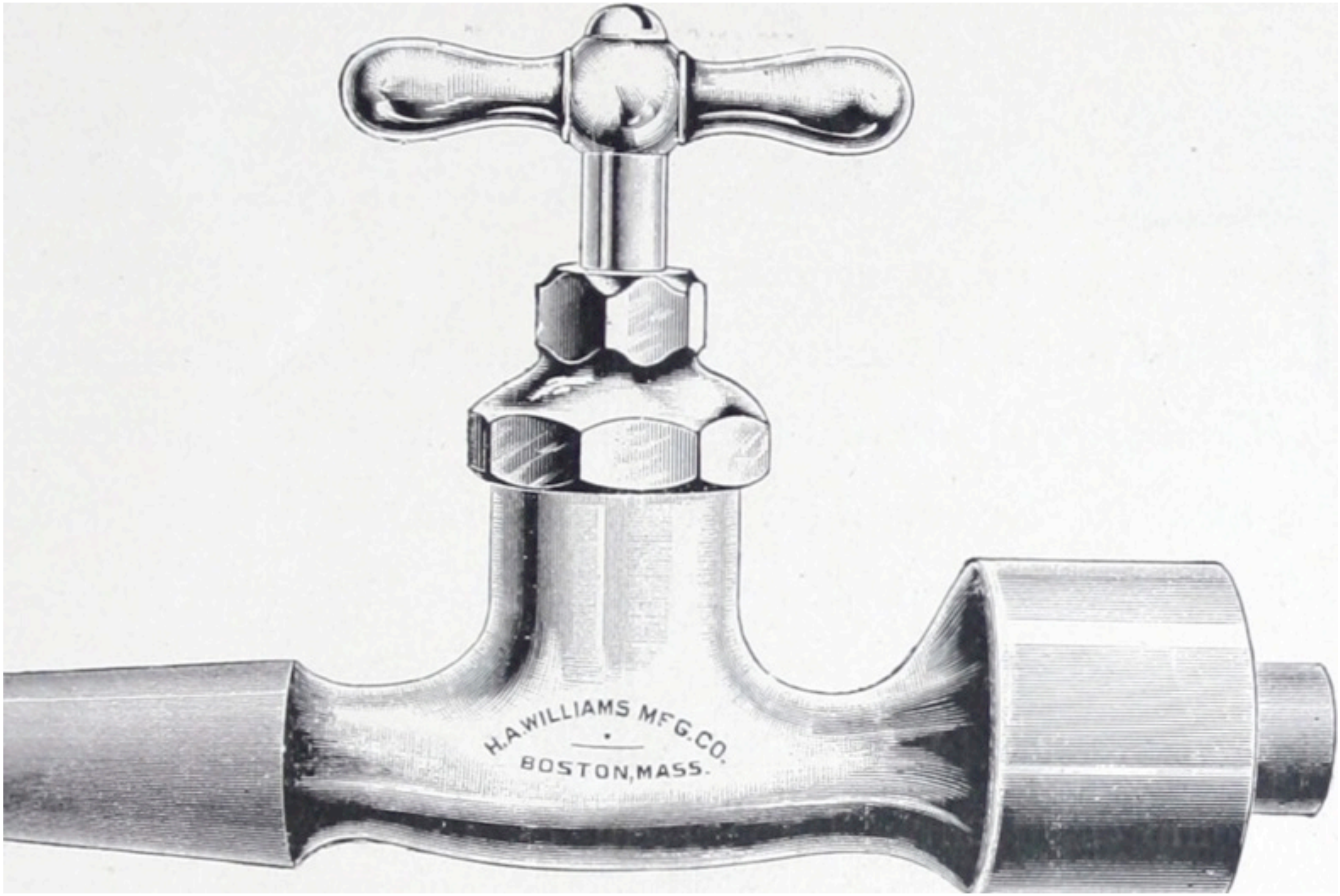
How did we fix it?

- **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



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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

```
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

```
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

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Scoping

- **Arrays are now destroyed when they go out of scope**
  - ‘begin’ statements and array slices no longer affect array lifetime

```
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

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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 formals
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

Unintented Consequences

- **Consider this example with a sparse array of int:**

```
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
```

Unintented Consequences

- **What about a sparse array of arrays?**

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

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

writeln(A[3]);
```

Unintented 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)
```

Unintented 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

Fixing It

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Fixing It

- **Changed the default intent for arrays…**
  …to 'ref' if the formal argument is modified in the function body
  …to 'const ref' if not

```
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:**

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

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

writeln(A[3]); // prints A[3]
```

- **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

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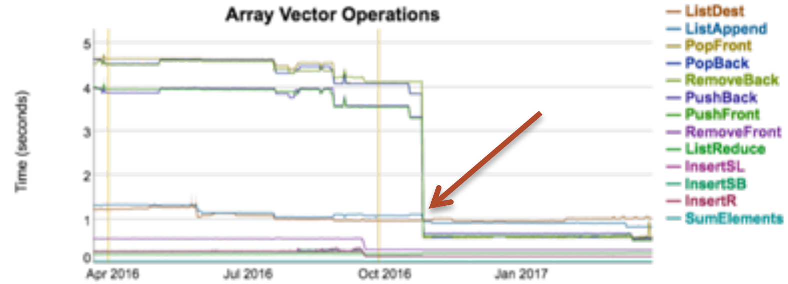
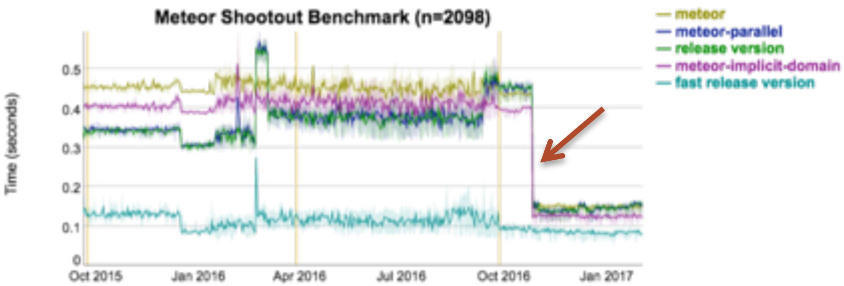
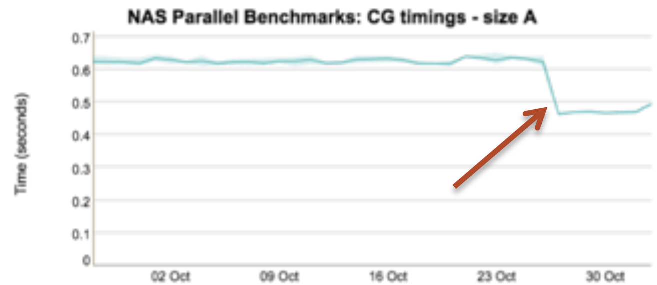
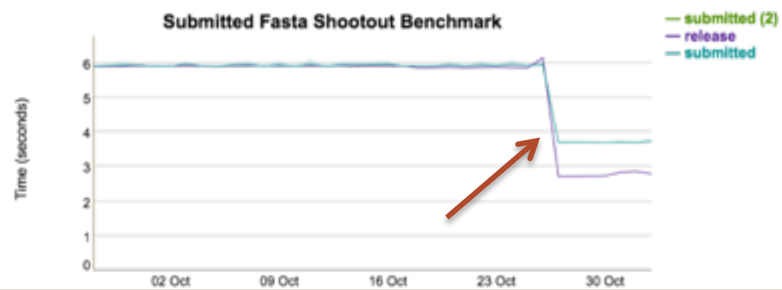
Reworking Array Memory Management

- **Substantial single-locale performance improvements**
  - up to 7x speedup in some cases



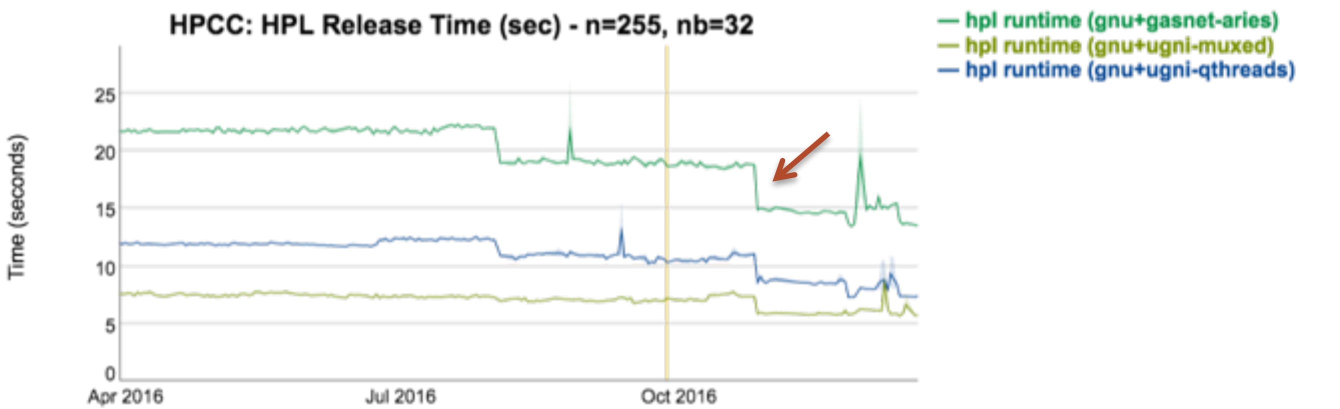


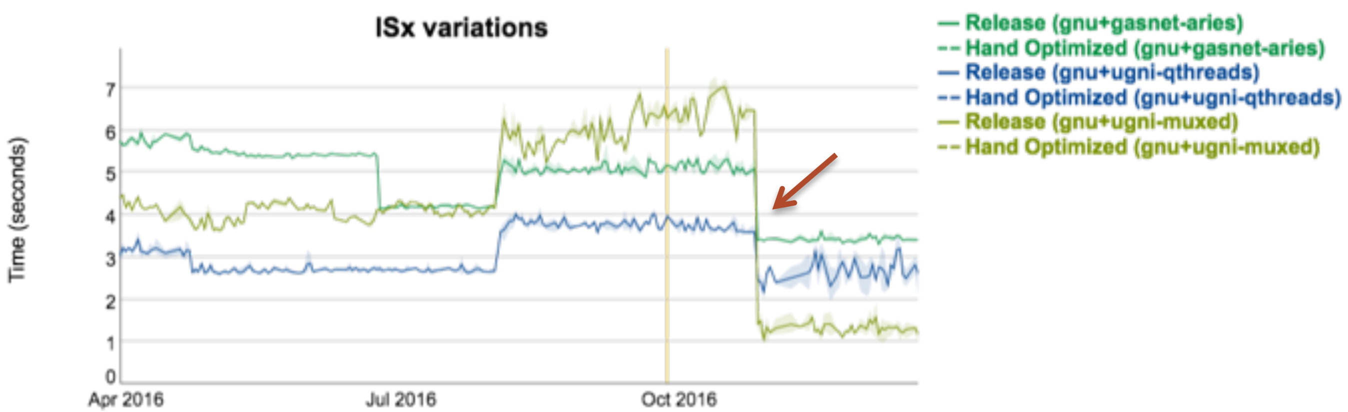




Reworking Array Memory Management

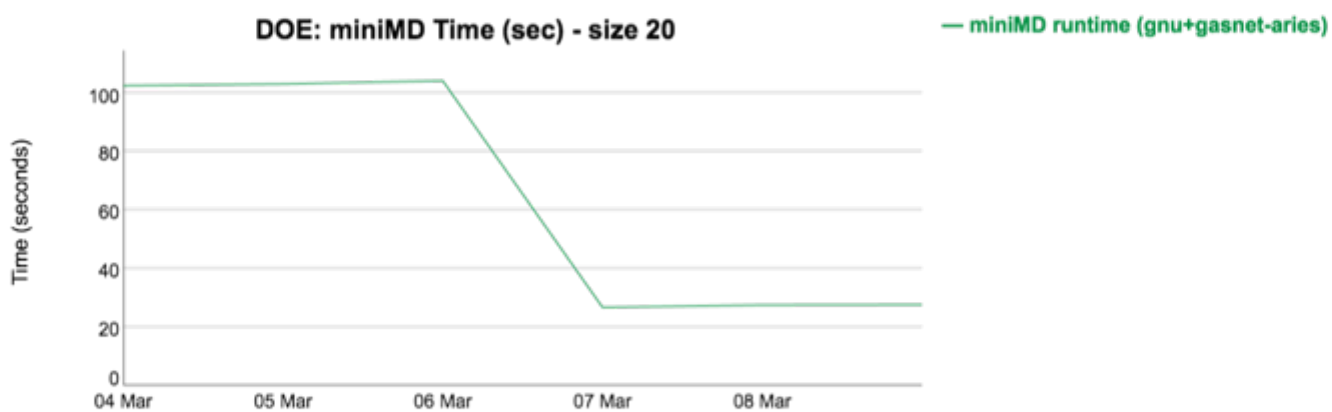
- **Some big multi-locale performance improvements**
  - up to 6x speedup





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

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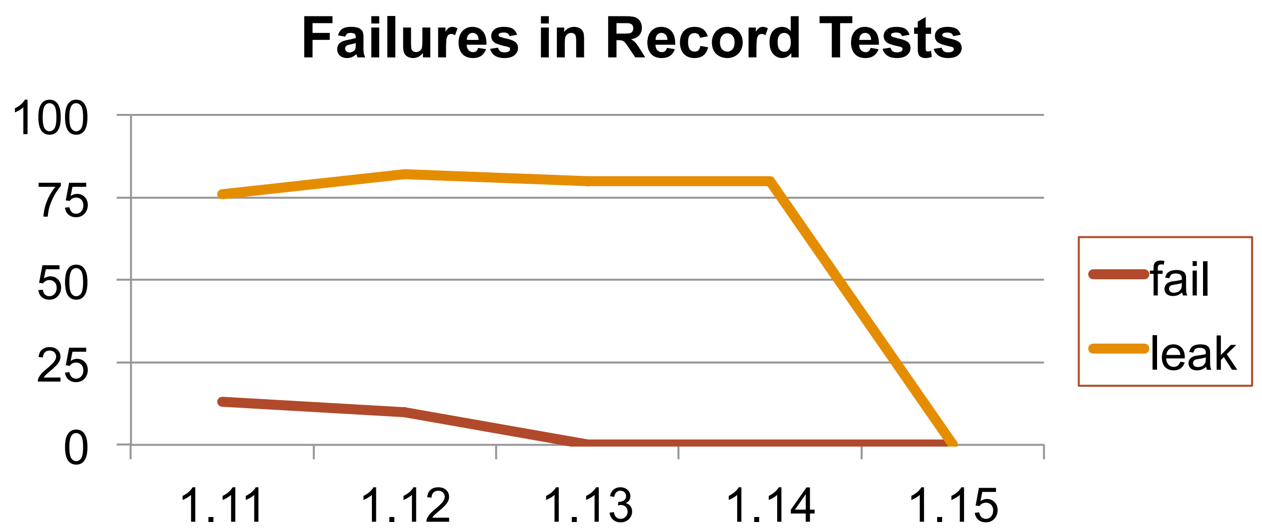
Building upon Record Memory Management

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



Tuples

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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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