Improvements to Arrays and Domain Maps

Chapel Team, Cray Inc.
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Outline

● Improved Array Memory Management
● Arrays Return By Value
● Array Default Argument Intent
● Array Views
● Deprecating Array Alias Operators ‘=>’
  ● Deprecating Array Aliases in Constructor Calls
  ● Deprecating Array Aliases in Declarations
● BlockCyclic Improvements
● Array/Domain Shape Methods
● Other Array / Domain Map Improvements
Improved Array Memory Management
Array Memory: Overview

● What is the problem?
  ● Array memory management was incorrect and slow

● Why do we have this problem?
  ● Original semantics of arrays required reference counting

● How did we address the problem?
  ● Language changes
  ● Leveraging improved semantics

● What is the result of this work?
  ● Huge reduction in leaks, good performance impact
Array Memory: Background

- **Array memory management has been problematic**
  - memory leaks
  - performance overhead

- **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!
    ```
Array Memory: How did we get here?

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
Array Memory: This Effort

- **Changed array behavior to solve these problems**
  - arrays are now returned by value by default
    - see next section for details
  - arrays are now freed when they go out of scope
    - ‘begin’ statements, array slices no longer extend array lifetime

- **New semantics do not require reference counting**

- **Re-implemented array, domain, distribution types to:**
  - remove array reference counting
  - free distributed objects
  - reduce number of special cases in the compiler

- **Improved tuple semantics in support of this effort**
  - see subsequent section for details
Array Memory: Language Changes

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

```haskell
proc badBegin() {
  var A: [1..10000] int;
  begin {
    A += 1;
    A += 1;
  }
  // User error: A destroyed here at function end, but the begin could still be using it!
}
```

- A new CHIP describes improved record / array behavior:
  - CHIP 13: When Do Record and Array Copies Occur?
Array Memory: Impact on Leaks

- Dramatically reduced memory leaks
  - Closed biggest source of memory leaks
    - e.g., PTRANS benchmark went from leaking 800MB to 0 bytes
  - Distributed arrays no longer leak
Array Memory: Impact on Performance

- Substantial single-locale performance improvements
- up to 7x speedup in some cases
Array Memory: Impact on Performance

- Caused a few performance regressions
- Follow-on work resolved these regressions
  - Remote Value Forwarding improvements
  - Wide pointer optimization improvement

---

--no-local

multi-locale, GASNet-MPI
Array Memory: Impact on Performance

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

**HPCC: HPL Release Time (sec) - n=255, nb=32**

**ISx variations**

- hpl runtime (gnu+gasnet-aries)
- hpl runtime (gnu+ugni-muxed)
- hpl runtime (gnu+ugni-qthreads)

- Release (gnu+gasnet-aries)
- Hand Optimized (gnu+gasnet-aries)
- Release (gnu+ugni-qthreads)
- Hand Optimized (gnu+ugni-qthreads)
- Release (gnu+ugni-muxed)
- Hand Optimized (gnu+ugni-muxed)
Array Memory: Next Steps (Implementation)

- **Address remaining record memory management issues:**
  - returning a 'ref' intent formal by value should copy but doesn't
  - totally generic member variables can leak
  - variables in an iterator can leak when ‘break’ing from the calling loop

- **Optimize away copies when possible**
  - benefits both arrays and records such as 'bigint'
  - in particular, improve upon
    - assignment or passing by 'in' intent
      - …from a call returning an array by value
Array Memory: Next Steps (Language Design)

● Develop strategies for tricky design issues:
  ● how to describe when compiler can omit a copy?
  ● how can user types opt-in to aggressive copy elimination?

● Update language specification to describe:
  ● when record/array copies occur
  ● tuple semantics in more detail
  ● function return is normally by-value
Arrays Return By Value
Array Returns: Background and This Effort

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

**This Effort:** Changed arrays to 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
```
Array Returns: Compatibility

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

```plaintext
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
```
Array Returns: Next Steps

- Describe array return behavior in language specification
- Revisit l-value rules for arrays
  - if f() returned a record by value, this would be an error:

```
ref B = f();
```

...but it is currently allowed when f() returns an array
Array Default Argument Intent
Array Intent: Background

● Historically, the default intent for arrays was 'ref'
  ● designed as a convenience for programmers
  ● avoids surprising programmers used to modifying array formals

● This design interacted poorly with return intent overloads
  ● return intent overloads allow different behavior on read and write
    ● e.g. writing the “zero” values of a sparse array is an error
    ● e.g. reading the “zero” values of a sparse array is fine
  ● combining this with 'ref' default intent created surprising behavior
    ● especially with arrays-of-arrays

● Not just a matter of accurate const-checking errors
  ● problems originally discovered studying miniMD performance
Array Intent: Motivation

Consider this example with a sparse array of int:

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

var A: [sps] int;

writeln(A[3]);  // outputs 0, the "zero" value
```
Array Intent: Motivation

- Behavior changes for an 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
Array Intent: This Effort

- **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;  
senetElementOne(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);
```

- **Fixed related bugs in the implementation**
Array Intent: Resulting Behavior

Motivating cases now work as you’d expect:

```haskell
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
Array Intent: Impact

- **Reduced a source of bugs and confusion**
  - makes the language more consistent and less surprising
  - still meets the original array intent design goals:
    - simple programs can be written without argument intents
    - avoids surprising programmers accustomed to modifying array formals

- **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
Array Views
Array Views: Background (Domain Maps)

Domain maps are “recipes” that instruct the compiler how to map the global view of a computation...

A = B + alpha * C;

...to the target locales’ memory and processors:
Domain Map Definitions

Domain Maps:

- recipes for implementing domains and their arrays
- come in two flavors:
  1. layouts:
     - target a single locale
     - specify memory layout
  2. distributions:
     - target multiple locales
     - specify distribution of indices to locales
     - typically implemented using a layout within the locale
- implemented using three classes ("descriptors"):  
  1. the domain map object itself
  2. an object for each domain implemented using that domain map
  3. an object for each array implemented using that domain
Domain Maps: Descriptor Interfaces

- **Domain Map Interfaces**
  - *domain map objects must specify:*
    - which locale owns a given index
    - ...
    - how to create domains

  - *domain objects must specify:*
    - how to iterate over indices
    - how to intersect with other domains
    - how to test for membership
    - ...
    - how to create arrays

- **array objects must specify:**
  - how to access the array’s elements
  - how to iterate over the array’s elements
  - ...

Sample Descriptors

const MyRMO = new dmap(new RMO(here.numCores, parStrategy.rows));

const D = {1..m, 1..n} dmapped MyRMO,
        Inner = D[2..m-1, 2..n-1];

var A: [D] real,
    AInner: [Inner] real;
Array Descriptors

```plaintext
const MyRMO = new dmap(new RMO(here.numCores, parStrategy.rows));

const D = {1..m, 1..n} dmapped MyRMO,
    Inner = D[2..m-1, 2..n-1];

var A: [D] real,
    AInner: [Inner] real;
```
Three “Array View” Operations

Slicing:

...A[lo1..#b, lo2..#b]... // refer to a b x b block starting at (lo1, lo2)

...A[... , i..i]... // refer to the ith column of A (as a 2D array)

Rank Change:

...A[... , i]... // refer to the ith column of A as a 1D array

Reindexing:

...A.reindex({0..m-1, 2..2*n + 2}); // use alternate indices to refer to A

Historically, domain map descriptors have implemented these operations as part of their standard interface
Problems with this Approach

- **Implementing these three views can be nontrivial**
  - typically the last things domain map authors write, if they ever do
  - most distributions have had restrictions in practice
    - e.g., “I can’t handle strided slices”
    - compile- or execution-time errors when encountered
  - current implementations typically use “closed form”
    - store result of view operations using the same descriptor format
Closed-form Slice Descriptor

const MyRMO = new dmap(new RMO(here.numCores, parStrategy.rows));

const D = {1..m, 1..n} dmapped MyRMO,
           Inner = D[2..m-1, 2..n-1];

var A: [D] real;
...A[Inner]...
Challenges with Closed-Form Approach

● Representations aren’t always well-suited for closed-form
  ● e.g., BlockCyclic distributions store a packed set of array blocks per locale
    
    ```
    const D = {1..n, 1..n} dmapped BlockCyclic(...);
    var A: [D] real;
    ```
  
  ● That representation isn’t well-suited for arbitrary slices:
    ```
    ...A[3.. by 7, i]...
    ```
  
  ● how to store the interference pattern between stride 7 and `numLocales`?
  ● how to represent this 1D slice as a packed set of 2D blocks?
Array Views: This Effort

This Effort:

- stop expecting domain maps to implement array view operations
- instead, introduce dedicated domain maps for these operations
  - have them implement the complete domain map interface
  - typically by forwarding to original descriptors

- e.g., for A[Inner]:
  - stop creating a new descriptor of A’s type
  - instead, create a descriptor that
    - represents a slice expression
    - refers to the descriptors for ‘A’ and ‘Inner’

- the following slides sketch the descriptors used for each operation
  - for each, the path that an access to that view takes is illustrated
Array View Slice Descriptor

\[
\text{const } D = \{1..m, 1..n\}, \\
\text{Inner} = D[2..m-1, 2..n-1];
\]

\[
\text{var } A: [D] \text{ real;} \\
\ldots A[\text{Inner}]\ldots
\]
Array View Slice Descriptor

**step 0:** compiler makes call to dsiAccess(ij)

**step 1:** bounds-check dsiMember(ij)

**step 2:** forward dsiAccess(ij)

```
const D = {1..m, 1..n},
        Inner = D[2..m-1, 2..n-1];

var A: [D] real;
...A[Inner][ij]...
```
Array View Rank-Change Descriptor

```
const D = {1..m, 1..n},
        Inner = D[2..m-1, 2..n-1];

var A: [D] real;
...A[.., 3]...
```
Array View Rank-Change Descriptor

**step 0:** compiler makes call to dsiAccess(i)

```
const D = {1..m, 1..n},
    Inner = D[2..m-1, 2..n-1];

var A: [D] real;
...A[., 3][i]...
```
Array View Reindex Descriptor

const D = {1..m, 1..n};

var A: [D] real;
...A.reindex({0..m-1, 1..2*n by 2})...
const D = {1..m, 1..n};

var A: [D] real;

...A.reindex({0..m-1, 1..2*n by 2})[2,5]...
Domain / Domain Map Views

- Rank-change and Reindex raise additional challenges
  - Motivating example:
    ```
    const D = {1..n, 1..n} dmapped Block(...);
    var A: [D] real; // A is a block-distributed 2D domain
    foo(A[.., i]);   // pass a 1D slice of A to foo()
    ```
    ```
    proc foo(X: [?Di]) {
      var B: [Di] real; // Di must be a 1D domain representing D’s ith column
      const S = {3..5} dmapped Di.dist; // Di.dist implies a domain map
      } // that can create new 1D domains aligned with A’s ith column
      // yet, the original 2D domain and distribution are ill-equipped to support these ops
    ```
  - Reindex operations have similar challenges
  - Historically, domain map descriptors have had to support these ops
    - represented additional complexity for the author, often unimplemented

- Solution: Create views for domains and domain maps as well
Array Views: Impact

● **Simplified domain map standard interface**
  ● eliminated the need for these previously required routines:
    ```
    [array].dsiSlice()
    [array].dsiRankChange()
    [array].dsiReindex()
    [dom].dsiBuildRectangularDom()
    [dist].dsiCreateRankChangeDist()
    [dist].dsiCreateReindexDist()
    ```
  ● doing so eliminated a lot of complex code
  ● as well as several previously unsupported cases:
    ● strided reindexing of cyclic arrays
    ● rank-change slicing of block-cyclic arrays
    ● reindexing of block-cyclic arrays
    ● ability to mix stridable- and non- in slicing Dimensional arrays
    ● slices of block-cyclic arrays failed to bounds-check
    ● ...

  ...
Array Views: Impact

- **Improved performance / reduced communication**
  - several tests that count communications for array operations improved
  - saw performance improvements, particularly for remote slice idioms
    - e.g., MiniMD uses remote slices to transfer boundary conditions
  - this graph illustrates resulting improvement for 16 compute nodes:
  
  ![Graph showing DOE: miniMD Time (sec) - size 20](image)

Array Views: Impact

- **Enabled a more precise array indexing optimization**
  - Chapel 1.14 optimized array accesses using compiler analysis
  - Analysis known to be unstable w.r.t. unrelated arrays in the program
    - see “Array Indexing Optimization” slides in 1.14 release notes
  - Array views permit the optimization to be done in module code
    - simpler
    - more precise—no longer unstable w.r.t. unrelated arrays in the program

- **Creates distinct types for array view operations**
  - Arrays that “own” storage versus “alias” storage now more distinct
  - Improves ability to reason about and optimize such cases in compiler

- **Retired need for ‘=>’ in constructor context**
  - (see following section)
Array Views: Impact

- **Downside**: array view expressions now involve indirection
  - in closed-form, array views were as fast as arrays
  - (when the operation was supported and worked…)
  - now, routines tend to be forwarded to the original array
  - believe this is the right trade-off
  - but important to be aware of

- optimizations are possible
  - can squash stacked views
    - e.g., a slice of a slice of A can be stored as a slice of A
  - have already optimized common cases
    - e.g., we’ve manually optimized array views for default arrays

```
const D = {1..m, 1..n},
    Inner = D[2..m-1, 2..n-1];

var A: [0] real;
..A[Inner][13]..
```
Array Views: Next Steps

● **Though array views are implemented, some work remains**
  
  ● **case 1:** loss of locality for domains/distributions of reindexed arrays:

    ```
    const D = {1..n} dmapped Block(...);
    var A: [D] real;
    foo(A.reindex({0..n-1}));
    proc foo(X: [?D]) {
      forall i in D do
        writeln(here.id); // will always print 0 as D fails to preserve locality
    }
    
    ● **status:** reindex domain/dist. views drafted but not yet on master
    ```
Array Views: Status

- **Though array views are implemented, some work remains**
  - **case 2:** can no longer pass array views to default constructors:
    ```java
    class C {
        var X: [1..3] real;
    }
    var A: [1..100] real;
    var myC = new C(A[1..3]);
    ```
  - **reason:** compiler-generated constructor is too strict about types
    - slice-of-array no longer of identical type as array
  - **status:** planning to address with compiler-generated initializers
Array Views: Status

● Though array views are implemented, some work remains
  ● case 3: formal type queries + assertions changed in behavior:
    ```
    proc foo(x: ?t, y: t) {...}
    ```

    ```
    var A: [1..3] real, B: [1..10] real;
    // in 1.14, all of the following worked:
    foo(A, B[1..3]);       // no longer works in 1.15
    foo(A[1..3], B[1..3]); // no longer works in 1.15
    foo(B[1..3], A);       // still works in 1.15
    ```

  ● reason:
    ● slices and arrays had same type in closed form, now they don’t
    ● code that implements ‘?t’ inserts a copy
      ● copies of slices result in deep copies ⇒ seems to have the type of a new array
      ● so, all 3 cases want arg 2 to be an array rather than a slice
  ● status: bug; needs to be addressed
    ● probably by changing ?t implementation
Deprecating Array Alias Operators ‘=>’
Deprecating Array Alias Operators (=>)

- Array alias operators were supported in two contexts:
  - constructor calls
  - declarations

- Chapel 1.15 deprecated support for both of these cases
  - both represented special cases
  - neither was necessary any longer

- We’ll consider each case separately in the following slides
Deprecating Array Aliases in Constructor Calls
Distributions like ‘Block’ store a domain + array per locale
  ● use a default local domain/array for these variables

  ```
  class LocBlockArr {
    // class representing this locale’s local block
    type eltType;
    // element type of the array
    var locDom: LocBlockDom;
    // pointer to this locale’s local domain
    var myLocElts: [locDom.myLocInds] eltType;
    // this locale’s block
  }
  ```

For closed-form array views, this presented a challenge:
  ● consider the following slice of a block-distributed array:

  ```
  const D = {1..n, 1..n} dmapped Block(...);
  var A: [D] real;
  ...A[2..n-1, ..]...
  ```

  ● since slices alias their original arrays…
    ...the slicing expression’s ‘myLocElts’ must alias A’s ‘mylocElts’
  ● but it’s an array field—how can we make it alias another array?
in Constructors: Background

Historical approach:
- added support for using the array alias operator in constructor calls
- given:
  ```
  class LocBlockArr {
      type eltType; // element type of the array
      var locDom: LocBlockDom; // pointer to this locale’s local domain
      var myLocElts: [locDom.myLocInds] eltType; // this locale’s block
  }
  ```
- the following calls would make the ‘myLocElts’ field alias an existing array:
  ```
  var B: [1..10] real;
  var C = new LocBlockArr(myLocElts=>B);
  var myAslice = new LocBlockArr(myLocElts=>A.locArr.myLocElts);
  ```

Net result:
- supported closed form for such distributions
- added a lot of complexity to the compiler
- raised barriers to adding new generic fields to local arrays
=> in Constructors: This Effort

● Array views no longer rely on closed form representations
  ● i.e., aliasing is now done by aliasing ‘LocBlockArr’, not ‘myLocElts’

```java
class LocBlockArr {
    // class representing this locale’s local block
    type eltType;
    // element type of the array
    var locDom: LocBlockDom;
    // pointer to this locale’s local domain
    var myLocElts: [locDom.myLocInds] eltType;
    // this locale’s block
}
```

● Thus, supporting ‘=>’ in constructors is no longer needed
  ● Permits us to remove the related complexity from the compiler
    ● and to remove a special case in the language
  ● Makes it easier to add new generic fields to local arrays
=> in Constructors: Status and Next Steps

Status:

- deprecated ‘=>’ in constructors for 1.15
- plan to remove support for 1.16

Next Steps:

- Do we want to support ‘ref’ fields in classes/records?
  - or perhaps fields that can switch between ‘ref’ and ‘var’ via a param?
- Generalizes the “refer, don’t store” capability that this provided
  - yet in a way that is not array-specific
- No immediate need for this capability, but seems it could have utility
Deprecating Array Aliases in Declarations
Background:

- Chapel has included a special array alias initializer
  
  ```
  var A: [1..10] int;
  var B => A; // B refers to A’s elements
  var C: [0..9] => A; // C refers to A’s elements using indices 0..9
  C[0] = 10; // Now A[1] == 10
  ```

- Predated support for ‘ref’ declarations
  - Has felt increasingly like a redundant special-case since ‘ref’ was added

- Problematic in a few ways:
  - Fragile due to strict requirements on array types
  - Somewhat of a unique corner case in the language design

- **This Effort**: Deprecated ‘=>’ in favor of using ‘ref’ instead
  
  ```
  ref B = A;
  ref C = A.reindex({0..9});
  ```
Impact: Language is simpler
- Removed an array-only language feature
- Less special-case code in compiler

Next Steps: Finalize other array alias questions
- How does one return an array alias without a deep copy?

```plaintext
var A: [1..10] real;
proc foo() {
    return A[1..3];  // copies out by default due to new array return semantics
}
```
- But what if the user wants to return an alias to A?

```plaintext
proc foo() ref {
    // one proposal: use 'ref' for such cases, as with full arrays
    return A[1..3];
}
```
BlockCyclic Improvements
BlockCyclic: Background

- **BlockCyclic** is a standard Chapel distribution
  - Deals out blocks of indices in a round-robin fashion

Consider the following BlockCyclic domain:

```chapel
const D = {1..20, 1..20};
const Space = D dmapped BlockCyclic(startIdx=(1,1),
  blocksize=(4,4));
```

Distribution over 4 locales

```plaintext
L0    L1
L2    L3
```

4x4 blocks of indices
BlockCyclic: This Effort

- **Implemented intra-locale parallelism**
  - In 1.14, BlockCyclic only used one task per locale

- **Optimized indexing performance**
  - Use tuples instead of arrays for short-lived elements
  - Eliminated some incorrect multipliers
    - Fixed an out-of-bounds bug in the process
BlockCyclic: Impact

- 10x improvement for HPCC PTRANS
- 16 nodes on Cray XC
BlockCyclic: Status and Next Steps

Status:
- BlockCyclic is faster and more correct in 1.15

Next Steps:
- Continue improving indexing performance
- Improve privatization/caching
- Investigate wide-pointer overhead
- Investigate parallelism performance
  - Improvement is smaller than expected
Array/Domain Shape Methods
Shape Method

Background:
- Array/domain shapes are useful in many contexts (e.g., linear algebra)
  ```
  var A: [1..10, 3..30 by 10] real; // want a way of getting (10, 3) from A
  ```
- Getting array & domain shapes in a rank-neutral way was verbose:
  ```
  var shape: A.rank*(A.dim(1).idxType);
  for (i, r) in zip(1..shape.size, A.dims()) do
    shape(i) = r.size;
  ```

This Effort:
- Add array.shape and domain.shape methods
  - Works on all flavors of domains and arrays

Impact:
- Getting array/domain shapes has never been easier
  ```
  const shape = A.shape;
  ```
Other Array / Domain Map Improvements
Other Array / Domain Map Improvements

- For default arrays:
  - added support for targetLocales() queries
  - fixed bugs in ‘sublocale’ queries based on identity of calling locale
- Made .count() on arrays parallel by default
- Added comparator arguments to .sorted() on domains
- Reduced race conditions for associative-as-set operations
- Improved default hash functions for associative domains
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