Array, Domain, & Domain Map Improvements

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Block-Sparse Locality Improvements
Block-Sparse Locality: Background

Background:

- Block-distributed sparse arrays were introduced in Chapel 1.14
- Performance was far from ideal
  - a known issue / TODO: lack of privatization
  - a significant bug, revealed in Azad and Buluç’s CHIUW 2017 paper, *Towards a GraphBLAS Library in Chapel*:

preferred, high-level version:
```chapel
def unaryOp(a)
```
```chapel
def spArr
```
```chapel
def forall a in spArr do
  a = unaryOp(a);
```

lower-level workaround:
```chapel
def locArr
```
```chapel
def coforall locArr in locArrs do
  on locArr do
    def myElems
    ```
```chapel
def forall a in locArr.myElems do
  a = unaryOp(a);
```
Block-Sparse Locality: This Effort

This Effort:

- added privatization to Block-Sparse domains/arrays
  - privatization: localizing key descriptors to each target locale
  - contributed by Engin Kayraklioglu (GWU)
- fixed the bug revealed by CHIUW paper
  - parallel array iterator had the wrong “on-clause”, ran everything locally

```
- coforall locA in locArr do on LocArr {
+    coforall locA in locArr do on LocA {

    // forward to sparse standalone iterator
    for i in locA.myElems._value.these(tag) {
        yield i;
```

- unfortunately, not reported prior to publication, so not fixed for Chapel 1.15
## Block-Sparse Locality: Impact

**Impact:**
- simple loops on a 1000 x 1000 matrix, 10% sparse, 4 locales

```plaintext
forall ij in SD do
    SA[ij] = ...;

forall a in SA do
    a = ...;
```

### Results

<table>
<thead>
<tr>
<th></th>
<th>ons</th>
<th>gets</th>
<th>puts</th>
<th>time (100 trials)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.15</td>
<td>3,675,000</td>
<td>0</td>
<td>0</td>
<td>107.44 sec</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>3,675,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>225,009</td>
<td>75,000</td>
<td>15.37 sec</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>4,227,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.162 sec</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0193 sec</td>
</tr>
</tbody>
</table>

**Note:**
- The table compares the performance of accessing elements in a sparse matrix. The first loop accesses elements directly, while the second loop accesses them through a sparse array. The results show significant improvements in time for sparse accesses.
Block-Sparse Locality: Status and Next Steps

Status:
- Block-Sparse domains and arrays are now much more scalable

Next Steps:
- Further evaluation and tuning of sparse operations
Replicated Distribution Improvements
Replicated: Background

Background:

- Chapel has long supported a ‘Replicated’ distribution
  - concept: each target locale stores the entire domain/array (a ‘replicand’)
  - for example, each locale would store an $n$-ary domain/array given:
    ```chapel
    const D = {1..n} dmapped ReplicatedDist();
    var A: [D] real;
    ```

- Certain aspects of its behavior have been surprising / unusual
  - e.g., the following loop traversed all elements in all replicands
    ```chapel
    forall a in A do ... // does $O(n*\text{numLocales})$ work rather than $O(n)$
    ```
  - e.g., ‘.size()’ would return ‘$n*\text{numIndices}$’ rather than simply ‘$n$’

- Other minor pain points:
  - no way to easily access another locale’s replicand
  - distribution class was named ‘ReplicatedDist’, as was module
    - contrast with ‘Block’ distribution defined in ‘BlockDist’ module
  - target locale array had an unusual “consistency” requirement
Replicated: Consistency Improvements

This Effort: Improved naming and behavior
- Replaced 'ReplicatedDist' with 'Replicated'
- Make 'Replicated' operations refer to local data only
- Consider the following declarations, running on two locales:

```plaintext
const D = {1..5} dmapped ...
var A: [D] real;
```

<table>
<thead>
<tr>
<th>code</th>
<th>ReplicatedDist (1.15)</th>
<th>Replicated (1.16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>for[all] i in D do... for[all] a in A do...</td>
<td>iterated over all 10 indices / elements, generating communication</td>
<td>iterates over 5 indices / local elements</td>
</tr>
<tr>
<td>D.size() / A.size()</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>writeln(D);</td>
<td>{1..5} replicated over LOCALE0 LOCALE1</td>
<td>{1..5}</td>
</tr>
<tr>
<td>writeln(A);</td>
<td>LOCALE0: 0.0 0.0 0.0 0.0 0.0 LOCALE1: 0.0 0.0 0.0 0.0 0.0</td>
<td>0.0 0.0 0.0 0.0 0.0</td>
</tr>
</tbody>
</table>
Replicated: Other improvements

This Effort: Implemented other improvements

- “Added ‘.replicand()’ method to access a remote locale’s copy
  - e.g., could simulate old writeln(A) behavior via:
    ```chapel
    for loc in Locales {
      writeln(loc, "::")
      writeln(A.replicand(loc.id));
    }
    ```

- Removed “consistency” requirement on target locale set

- Added a Replicated-specific primer, improved documentation
  - see: [http://chapel.cray.com/docs/1.16/primers/replicated.html](http://chapel.cray.com/docs/1.16/primers/replicated.html)
Replicated: Status and Next Steps

Status:

- Preserved ‘ReplicatedDist’ for 1.16
  - maintains backwards compatibility for existing users
  - generates a deprecation warning
  - will be retired in 1.17

- “But what if I liked the old behavior?”
  - can still get it via manual rewrites:
    ```
    coforall loc in Locales do // implement old forall behavior
        on loc do
            forall i in D do ...
    ```

Next Steps:

- Gain additional experience with ‘Replicated’ and improve it as needed
Associative Array Locking Improvements
Associative Locking: Background

**Background:**

- Traditionally, associative array accesses have been guarded by locks

  ```
  proc AssocArray.access(idx) ref {
      lock$ = true; // take lock
      ref elt = ...; // take reference to element
      lock$; // release lock
      return elt; // return reference
  }
  ```

- Presumably to avoid races in the event that the array was being resized

  ```
  cobegin {
      Age[“abe”] += 1; // update an existing person’s age
      People += “billy”; // add a new person, growing the array
  }
  ```

- However, such guards don’t actually provide safety
  - The array could still be resized between the return of the ref and its use
  - The lock would need to surround the entire assignment to be effective
Associative Locking: This Effort

This Effort:
- remove locking on associative array accesses
- makes them more similar to other array types
  - e.g., rectangular arrays are also subject to such races
    ```c
    cobegin {
        A[i,j] += 1;
        D = {1..2*m, 1..2*n};
    }
    ```
- such cases have always been considered the user’s responsibility
 Associative Locking: Impact

Impact:

- improved performance for cases using associative array accesses
Associative Locking: Next Steps

Next Steps:
- Look into techniques to improve safety in such cases
  - compiler analysis?
  - (expensive) opt-in execution-time techniques?
Array View Improvements
Array Views: Background

Background:

- Chapel 1.15 introduced the concept of array views
  - implement array slicing, rank-change, and reindexing via indirection
  - made these operations more robust
  - simplified authoring new domain maps
- Some work was left unfinished in 1.15
  - domains/dists of reindexed distributed arrays did not preserve distribution
  - domains/dists of rank-change / reindex arrays were only stored on locale 0

```chapel
var MyDistArr: [{1..m, 1..n} dmapped Block(...)] real;
ref ZeroBasedArr = MyDistArr.reindex({0..#m, 0..#n});
foo(ZeroBasedArr);
proc foo(X: [?D]) {
  var Y: [D] real; // Y was not distributed as you’d think it would be
  on Locales[2] {
    const s = D.size; // locale 2 had no local copy of D ⇒ comm. required
  }
}
```
Array Views: This Effort

This Effort:
- Fixed the aforementioned issues
- domains and distributions of distributed array views...
  - ...preserve locality
  - ...are privatized

```plaintext
var MyDistArr: [{1..m, 1..n} dmapped Block(...)] real;
ref ZeroBasedArr = MyDistArr.reindex({0..#m, 0..#n});
foo(ZeroBasedArr);
proc foo(X: [?D]) {
    var Y: [D] real;  // Y is now distributed like X / MyDistArray
    on Locales[2] {
        const s = D.size;  // locale 2 has a local copy of D; can compute locally
    }
}
```
Array Views: Impact and Next Steps

**Impact:**
- Array views of distributed arrays behave as you’d expect
- Communication requirements have been reduced in such cases

**Next Steps (see 1.15 release notes for details):**
- Restore ability to pass array views to default initializers
- Fix type query behavior for array views
Compressed Sparse Row/Column Layouts (CSR/CSC)
**Background:** Chapel has supported CSR layouts, but not CSC

- CSR (Compressed Sparse Row) supported by LayoutCSR
- CSC (Compressed Sparse Column) has not been supported
  - useful for interoperability, efficient CSR * CSC matrix multiplication, …

**This Effort:**
- Generalized LayoutCSR to support CSC as well:
  
  ```achsen
  // CSC specified through param-argument
  var cscD: sparse subdomain(D) dmapped CS(compressRows=false);
  // CSR is the default
  var csrD: sparse subdomain(D) dmapped CS();
  ```

**Status:**
- Replaced LayoutCSR with LayoutCS
- Deprecated LayoutCSR (will be removed in future releases)

**Next Steps:** improve performance of CSR, CSC layouts
Optimizing Sparse bulkAdd
Sparse bulkAdd

**Background:** Sparse domains support bulkAdd()
- Adds many new indices at once for efficiency

**This Effort:** Optimize bulkAdd() when domain is empty
- Contributed by Engin Kayraklioglu

**Impact:** Improved performance for some use cases:

---

Time to create a scale-20 Graph500 domain (seconds)

- **Pre-sorted Indices**
  - Before: [Time]
  - After: [Time]

- **Unsorted Indices**
  - Before: [Time]
  - After: [Time]
Bulk Array Expansion
Bulk Array Expansion

**Background:** Array expansion interfaces had an issue

- Expanding arrays using array arguments resulted in promotion
- The promotion pushed new elements in an undefined order:

```javascript
var A = [1,2,3];
A.push_back([4,5,6]); // Non-deterministic results, e.g. [1, 2, 3, 5, 6, 4]
```

**This Effort:** Added array overloads for extension methods

- New overloads:

  ```javascript
  array.push_back(arr: [])
  array.push_front(arr: [])
  array.insert(pos: idxType, arr: [])
  ```

- Optimized to grow array memory only once

**Impact:** Arrays can append, prepend, and insert in bulk

- The following code behaves as expected:

```javascript
var A = [1,2,3];
A.push_back([4,5,6]); // A is now: [1,2,3,4,5,6]
```
Parallel Array Initialization
Parallel Array Initialization

**Background:** We initialize numerical arrays in parallel
- To get correct first-touch on NUMA systems

**This Effort:** Initialize POD (plain old data) arrays in parallel
- For example: records with numeric fields, tuples, etc.

**Impact:** No visible improvements in our performance graphs
- Significantly improved performance of a user’s nbody simulation

**Next steps:** Extend parallel initialization to all arrays
- Including arrays-of-arrays
- Also want to permit users to override initialization strategy
Other Array, Domain, Domain Map Improvements
Other Array, Domain, Domain Map Changes

- Added a version of reindex() that takes range arguments
  - previously required a domain argument
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