Benchmarks, Performance Optimizations, and Memory Leaks

Chapel Team, Cray Inc.
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Outline

● Benchmark Improvements
  ● LCALS: Livermore Compiler Analysis Loop Suite
  ● MiniMD Benchmark Improvements
  ● The ISx Benchmark in Chapel

● Performance Optimizations
  ● Bulk Transfer Improvements
  ● Local On-Statements
  ● Numa maxTaskPar Fix
  ● Array-as-Vector Improvements
  ● Reduction Performance Improvements
  ● Performance of LLVM Back-End
  ● Anonymous Counted Range Optimization

● Memory Leak Improvements
  ● Lexical Scoping Improvements
  ● Evaluation of Current Memory Leaks
LCALS: Livermore Compiler Analysis Loop Suite
LCALS: Background

- **LCALS: Livermore Compiler Analysis Loop Suite**
  - Loop kernels designed to measure compiler performance
  - Developed by LLNL
  - [https://codesign.llnl.gov/LCALS.php](https://codesign.llnl.gov/LCALS.php)

- Three loop subsets (30 kernels total)
  - Subset A: Loops representative of application codes
  - Subset B: Simple, basic loops
  - Subset C: Loops extracted from “Livermore Loops coded in C”

- Each kernel is run for three sizes (Short, Medium, Long)

- Each kernel is implemented in a number of “variants”
  - RAW (traditional C usage), OpenMP, C++ template-based, etc.
LCALS: This Effort

- **Port LCALS framework to Chapel**
  - ~2400 lines of Chapel framework code

- **Port the RAW and RAW+OpenMP kernels to Chapel**
  - RAW: All 30 kernels ported and getting correct results
  - RAW+OMP: All 11 kernels ported and correct
    - RAW+OMP kernels are a modified subset of the RAW kernels
  - ~2200 lines of Chapel kernel code

- **Compare performance vs. reference versions**
  - Executed on one Cray XC40 compute node
  - 24 Intel Xeon cores per node
  - Compiled with: gcc 5.3.0
  - The following graphs show results for the “Long” size
LCALS: Performance Comparison

A Loops (Application Inspired)

Normalized time – serial reference is 1.0

- **Reference**
- **Serial Chapel**
- **OMP**
- **Parallel Chapel**

```
chpl --fast
--no-ieee-float

g++ -Ofast -fopenmp
```
LCALS: Performance Comparison

B Loops (Basic Loops)

Normalized time – serial reference is 1.0

- init3
- muladdsub
- if_quad
- trap_int

Normalized time

<table>
<thead>
<tr>
<th></th>
<th>init3</th>
<th>muladdsub</th>
<th>if_quad</th>
<th>trap_int</th>
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<tbody>
<tr>
<td>Reference</td>
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<tr>
<td>Serial Chapel</td>
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<tr>
<td>Parallel Chapel</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Commands:
- chpl --fast --no-ieee-float
- g++ -Ofast -fopenmp

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LCALS: Performance Comparison

C Loops I (Livermore Loops)

Normalized time – serial reference is 1.0

chpl --fast
--no-ieee-float

g++ -Ofast -fopenmp
LCALS: Performance Comparison

C Loops II (Livermore Loops)

Normalized time –
serial reference is 1.0

- chpl --fast
  --no-ieee-float

- g++ -Ofast -fopenmp
LCALS: Status

- RAW and RAW+OMP kernels ported

- Performance is hit-or-miss
  - serial performance:
    - ~half of the serial kernels are competitive with the reference versions
    - a handful are >2x off (e.g. first_sum, couple, …)
    - the remainder need some attention
  - parallel performance:
    - generally lagging significantly relative to OpenMP

- Tracking performance of serial RAW kernels nightly
  [link]

- Chapel LCALS port included in the 1.13 release
  [link]
One cause of missing LCALS performance is known:
- Chapel uses an integer multiply for an array’s innermost dimension
- Unnecessary for typical arrays, only more advanced ones
  - e.g., rank-change, reindexing of strided slices, …
- For typical cases, adds overhead relative to C
  - Ongoing work is striving to eliminate multiplies in these cases
- Meanwhile, can be squashed manually using a config param
  - results in dramatic serial performance improvements for most loops:
LCALS: Next Steps

- Eliminate inner multiplies when unnecessary
- Understand causes of remaining performance differences
  - Focus on serial outliers, parallel cases
  - Compare vectorization of Chapel code with reference versions
  - Identify other overheads in generated code
- Get the parallel kernels into nightly performance testing
- Explore more elegant Chapel loop expressions
  - Use whole-array operations, array slicing, etc.
MiniMD Benchmark Improvements
MiniMD: Background

- **MiniMD: “Mini Molecular Dynamics”**
  - Proxy application from Sandia’s Mantevo group
  - Represents key idioms from real applications

- **Initially written as an intern project in 2013**
  - First major exploration of stencil codes in Chapel
  - Utilizes a custom variant of the *Block* distribution: *StencilDist*
  - Available in the release since that summer:
    $\text{CHPL\_HOME/examples/benchmarks/miniMD}$

- **Largely untouched since then**
  - Until now!
MiniMD: Correctness/Style Improvements

For this release...

- **Fixed bounds-checking bugs**
  - Incorrect logic in non-periodic cases
  - Incorrect bounds-checking with RAD optimization

- **Fixed the iterator that yields ghost/fluff/boundary cells**
  - Failed to correctly yield all overlapping regions on each locale

- **Switched to reduce-intents instead of atomics**
  - When first written, reduce intents did not exist
  - Using atomics is ugly and diverges from the reference
MiniMD: Performance Improvements

- **Improved parallelization for the exchange step**
  - Implemented in *StencilDist*’s `updateFluff()` method
  - Comprises most of the communication at scale

- **Leveraged forall-intents to reduce communication**
  - Used the ‘in’ intent to copy data across locales just once
MiniMD: Impact

- Stencil distribution is better overall
  - Fewer correctness issues
  - Special features are faster

- ~25% performance boost
  - 16-node Cray XC results:
MiniMD: Next Steps

● Improve Stencil distribution performance further
  ● Address known issues with array-of-arrays
  ● Leverage bulk transfer optimization

● Stencil distribution improvements
  ● Strive for more elegant ways to use this distribution
  ● Explore promotion of StencilDist to $CHPL_HOME/modules/dists/
  ● Clarify relationship between StencilDist and BlockDist (unify?)
The ISx Benchmark in Chapel
ISx: Background

● **ISx: Scalable Integer Sort benchmark**
  ● modern replacement for NPB IS to address its shortcomings
  ● developed at Intel, published at PGAS 2015: paper slides
  ● computation style:
    ● local SPMD-style computation with barriers
    ● punctuated by all-to-all bucket exchange pattern

● **SHMEM and MPI reference versions available on GitHub**
  https://github.com/ParRes/ISx

● **A good case study for Chapel**
  ● a common parallel pattern for distributed memory programming
ISx: This Effort

- **Ported ISx to Chapel**
  - Initial port co-developed with Jacob Hemstead, an author of ISx

- **Developed multiple variations in different styles**
  - Pure SPMD with coforalls
    - Most similar to the SHMEM reference version
  - “Global view” with locales, atomics, and forall loops

- **Investigate performance bottlenecks**
  - All graphs shown here were gathered on 16 nodes of Cray XC
At scale, the exchange step takes most of the time
- Expressed in Chapel via assignments between array slices
- Ought to benefit from bulk transfer optimization

Bulk transfer optimization wasn’t firing as expected
- Thwarted by overly-conservative runtime check, now fixed
- (see upcoming Bulk Transfer slides for more detail)
ISx: Performance – Atomics

- Global-view Chapel is slower than the SPMD variation
  - by up to 4x!

- Likely due to atomics
  - Global-view uses atomics to coordinate between forall-loop iterations
  - SPMD uses serial for loops without atomics
On Crays using ‘ugni’, overhead of atomics is even worse

- ‘ugni’ defaults to network atomics
- slow compared to processor atomics if only used locally, as in much of ISx
- 4x worse than GASNet version on previous slide:

- forcing processor atomics via CHPL_NETWORK_ATOMICS closes this gap

Future work:

- automatically optimize atomics that are only used locally
- add user-oriented capability to request local-only atomics
Manually optimized user-level code:

- Many loops contain loop-invariant common sub-expressions

```plaintext
for i in 0..#myBucketSize do
    myLocalKeyCounts[allBucketKeys[taskID][i]] += 1; // loop-invariant
```

- Manually hoisting such expressions had a huge impact

```plaintext
ref myBucket = allBucketKeys[taskID];
for i in 0..#myBucketSize do
    myLocalKeyCounts[myBucket[i]] += 1;
```

- Compiler should automatically hoist such sub-expressions
ISx: Performance Summary

- **Have made progress, but still falling off at scale:**
  - Numbers gathered on Cray XC
  - Reference version is SHMEM

- **Main bottleneck: exchange step**
  - Poor array slicing performance
  - Possible barrier performance issue
  - Plus a handful of other issues…
ISx: Status and Next Steps

Status:
- Chapel port of ISx released with 1.13
  - Just the SPMD variation for now:
    $CHPL\_HOME/examples/benchmarks/isx/
  - Exhibits many performance and scalability issues

Next Steps:
- Continue performance evaluation and improvements:
  - Optimize slicing
  - Eliminate reference counting
  - Improve atomics and locality
  - Evaluate and optimize barriers
  - Address other miscellaneous issues
- Reduce gaps between Chapel and reference, global-view and SPMD
  - Focus on SPMD vs. reference first since computation is naturally SPMD
Bulk Transfer Improvements
Bulk Transfer: Background

- Array assignment looks something like this:
  - Implemented within our internal modules (simplified):
    ```clojure
    proc = (ref A: [], B: []) {
        if compatibleTypes(A, B) && isContiguous(A, B) then
            bulkTransfer(A, B); // implemented with memcpy(), get(), or put()
        else
            forall (a, b) in zip(A, B) do a = b;
    }
    ```

- Typically, one big GET/PUT is better than many small ones
  - `bulkTransfer()` above is designed to handle such cases
  - Some benchmarks stand to benefit greatly
    - e.g., ISx
Bulk Transfer: This Effort

- Found cases where optimization didn’t fire as expected
  - Investigated and diagnosed those cases
  - Removed an incorrect / overly-conservative check in isContiguous():
    - Checked whether sliced arrays started at the beginning of the actual array:

```cpp
var A, B : [1..20] int;

// Starts at ‘1’, successfully bulk transfers
A[1..10] = B[1..10];

// Starts halfway, bulk transfer did not fire in 1.12 (but could’ve!)
// Fixed in 1.13
A[10..20] = B[10..20];
```
Bulk Transfer: Impact

- Significantly improved ISx exchange time
  - went from ~20s to ~2s (on 16 node XC)
Bulk Transfer: Next Steps

- Look for more opportunities to enable bulk transfer
  - Stencil distribution?
  - Other kinds of arrays?

- Investigate correctness/performance of strided transfer
  - Optimization contributed by Rafael Asenjo et al. (U. Malaga)
  - Enabled by ‘useBulkTransferStride’ config param
    - Currently disabled by default due to lack of familiarity, experience, testing
    - Goal: enable by default for next release
Local On-Statements
Local-On: Background

Background:

- On-statements are used to execute code on a given locale
  - Can also target sub-locales, as in the NUMA locale model

- Compiler inserts wide pointers for references spanning on-statements
  - Not necessary for sub-locales that share memory
  - Introduces needless overhead

- Compiler can’t generally distinguish sub-locales from top-level locales
Local-On: This Effort

This Effort:

● Introduce “local on” statements for sub-locales

  // execute on the first child locale
  local on here.getChild(0) {
    writeln("On sublocale ", here);
  }

● Generate runtime error if ‘local on’ leaves current node
  ● checks can be disabled by --no-local-checks, --no-checks, or --fast

  // Start on Locale 0, execute on last locale
  writeln("On Locale 0");
  local on Locales[numLocales-1] { // fails here for numLocales > 1
    writeln("On locale", here);
  }
Local-On: Impact

- Compiler can reduce overhead for local on-statements
- Better performance for wide-pointer-sensitive benchmarks
  - e.g. HPCC STREAM-EP

---

**HPCC STREAM-EP Performance (GB/s)**

- Correct # tasks
- Numa locale model
- Flat locale model

- max (default)
- avg (default)
- min (default)
- max (numa)
- avg (numa)
- min (numa)
Local-On: Status and Next Steps

Status:
- Local-on available in 1.13
- Used by ‘Range’ and ‘DefaultRectangular’ iterators
- Documented online: http://chapel.cray.com/docs/latest/technotes/local.html#the-local-on-statement

Next Steps:
- Use local-on in more places as we continue NUMA work
Numa maxTaskPar Fix
Numa maxTaskPar: Background and This Effort

Background:
● Numa locale model set top-level `here.maxTaskPar` incorrectly
  ● used `numSublocales` instead of runtime `chpl_task_maxTaskPar()`
  ● e.g., for two 12-core processors, `maxTaskPar` was 2 instead of 24
● For all loops create parallelism based on top-level `maxTaskPar`
  ● so, `maxTaskPar=2` resulted in only 2 tasks being created
● Resulted in abysmal performance for many benchmarks
  ● e.g., 16 GB/s for stream using ‘numa’ locale model vs. 84 Gb/s with ‘flat’

This Effort:
● Set top-level `here.maxTaskPar` correctly
  ● improved stream performance using ‘numa’ locale model to 63 GB/s
Numa maxTaskPar: Impact

- Resulted in dramatic performance improvements
Array-as-Vector Improvements
Array-as-Vector: Background and This Effort

Background:
- Vector operations on arrays were added in 1.10
  - A.push_back(val)
  - A.insert(pos, val)
  - A.pop_front()
  - etc.
- Each insertion or deletion triggered an array reallocation
  - Never wasted any space
  - But very slow!
  - (goal at that time was to get feature up and running, tune later)

This Effort: Amortize the allocation overhead ("later" is now!)
- Grow/shrink backing array by a factor of its current size
  - Factor is adjustable using a config param (defaults to 1.5)
- Size of backing array is invisible to the end-user
  - Size tracked by a range field added to arrays
Array-as-Vector: Impact

Execution Time (seconds)

Array-as-vec microbenchmarks

- push_back
- push_front
- insert rnd pos

~75x improvement in these benchmarks
Array-as-Vector Improvements: Impact

- Performance regression in RBC benchmark
  - Yet, RBC doesn’t use array-as-vector feature
  - Caused by (unused) range added to arrays to track allocated size
  - Motivates optimizing away range field when it won’t be used
    - potentially using ‘void’ field approach mentioned in language deck
Array-as-Vector Improvements: Next Steps

- Unify parallel safety vs. performance story across types
  - associative/sparse domains/arrays have similar tensions

- Make shrinking of buffer less aggressive
  - adds overhead for unfortunate push/pop pairs at boundary sizes

- Optimize the range field away for non-array-as-vec arrays
  - Arrays with rank ≠ 1
  - Arrays that are stridable
  - Analyze operations applied to given arrays, conservatively (?)

- Tune the default growth factor
Reduction Performance Improvements
Reduction Performance: This Effort

**Background:** Reduce expressions had a custom implementation

- independent of forall loop implementation in spite of similarities
  - e.g., standalone iterator was never considered
- performance lagged behind forall loops as well as a result

**This Effort:** Implement reductions using forall loops

- leverage reduce intents to perform reduction
  - only some built-in operations are handled at present
    - +, *, &, |, &&, ||, ^, min, max
- as before, use serial loop when parallel iterator is not available
**Reduction Performance: Impact – Reduction**

**Benchmark:** a single plus-reduction over a large array

- 1.12 to 1.13 speedup: 1.9x
- 1.11 to 1.13 speedup: 2.3x
- 1.11 and 1.12 very noisy
  - reporting just best times here
- measured on Linux server

- uses weak scaling
  (constant array size per locale)
- 1.12 to 1.13 speedup: 13x to 30x
- 1.11 is comparable to 1.12
  (overlaps on graph)
- measured on Cray XC40
Reduction Performance: Impact – CG

Benchmark: an iterative conjugate gradient benchmark
- earlier evaluation presented by Laura Brown at CHIUW 2015

- 1.12 to 1.13 speedup: 1.2x
- measured on Linux server

- multiple reductions, smaller arrays
- strong scaling (constant grid size)
- 1.12 to 1.13 speedup: 2x to 3.5x
- measured on Cray XC40
Reduction Performance: Next Steps

- Extend these improvements to other cases
  - arbitrary reduction operators
    - related to support for generalizing reduce intents (see “Language” slides)
  - zippered reductions
  - forall expressions

- Tune performance of forall loops
  - more efficient parallel iterators
    - e.g. tree-based spawning of tasks across locales
  - lower overhead specific to reduce intents
Performance of LLVM Back-End
LLVM Performance: Background

- Noticed significant performance gaps with --llvm back-end
  - especially for microbenchmarks

- e.g., array performance test was about 9x slower

- Started regular perf. testing to help investigate the issue
LLVM Performance: This Effort

- With --llvm, *link* step actually does target code generation
- Link step was missing optimization flags
- Simply adding these flags addressed the performance gap
LLVM Performance: Impact

- Saw significant performance improvements
LLVM Performance: Impact

- In some cases, --llvm now outperforms the C back-end
LLVM Performance: Next Steps

**Status:**
- LLVM and C back-ends are now generally competitive

**Next Steps:**
- Revisit --llvm-wide-opt for LLVM-based multi-locale optimization:
  - Start regular performance testing
  - Change from packed wide pointers to struct wide pointers
- Improve the LLVM IR that Chapel generates:
  - add loop vectorization hints in LLVM IR for forall/vectorizeOnly loops
  - Improve type-based alias analysis
  - Indicate when a load is to a const variable
  - Investigate enabling the Polly polyhedral optimizer
Anonymous Counted Range Optimization
Counted Ranges: Background and This Effort

Background:
● Counted ranges are convenient for iterating a certain number of times
  ● e.g. to loop 10 times just do:
    ```
    for i in 0..#10  /*instead of*/  for i in 0..10-1
    for i in lo..#10 /*instead of*/  for i in lo..lo+10-1
    ```

● Previous releases added an anonymous range optimization
  ● only optimized simple fully-bounded ranges
    ```
    for i in 0..9 do
    for i in 0..10-1 do
    for i in 0..10 by 2 do
    ```

● did not optimize low-bounded counted ranges
  ```
  for i in 0..#numIters do  // common in internal and user code
  ```

This Effort:
● Optimize low-bounded counted anonymous ranges
Counted Ranges: Impact

- Eliminated construction of low-bounded counted ranges

```plaintext
for i in 0..#10 do writeln(i);

previous generated code:
chpl_build_low_bounded_range(INT64(0), &call_tmp_l); // simple constructor
chpl___POUND(&call_tmp_l, INT64(10), &call_tmp_b);     // ~10 branches
low = (&call_tmp_b)->_low;
end = (&call_tmp_b)->_high;
for (i = low; i <= end; i += INT64(1))
  writeln(i);

now:
for (i = INT64(0); i <= INT64(9); i += INT64(1))
  writeln(i);
```
Anonymous Range Opt: Impact (continued)

- Minor speedup for test that happens to use nested ranges

- Nice generated code cleanup
  - but no major performance impact on most of our benchmarks
Lexical Scoping Improvements
Lexical Improvements: Background

Background:

- Chapel used to keep variables alive past lexical scopes
- For version 1.12, we decided to stop doing this
  - Reported on in the v1.12 release notes and language evolution docs
- However, many cases were still using the old semantics
  - Certain logical stack variables were allocated on the heap
    - Caused memory leaks in cases that were not reference-counted
    - Resulted in generated code complexity as well as overhead

```java
{
    var x: int; // Surprisingly, ‘x’ would be heap-allocated, just
    begin with (ref x) {
        // in case this ‘begin’ outlived x’s lexical scope.
        ...x...
    }
}

// Worse, it’d be leaked here because we’d never
// implemented reference counting for such cases.
```
Lexical Improvements: This Effort

This Effort:
- Tighten up such cases
- Stop allocating stack variables on the heap due to ‘begin’ statements

```plaintext
{  
  var x: int;  // ‘x’ is now stack allocated.
  begin with (ref x) {  // A reference to ‘x’ is now taken for the ‘begin’.
    ...x...
  }
}

// Like any other stack variable, ‘x’ is freed here.
// Any task still referring to ‘x’ is a user error
```
Lexical Improvements: Impact

- Eliminated all heap-converted data leaks in nightly testing
- Minor impact in our total overall leaks
  - Not surprising given how rarely such cases come up...
    - ‘begin’ is not used extensively in our test system
    - Even when it is, stack variables typically use default intent (const copy-in)
      - i.e., previous task intent work already closed most such leaks

```
diff --git a/memleaks.2015-10-02.nightly.log b/memleaks.2015-10-07.nightly.log
index 0fde8a2..fc2a0db 100644
--- a/memleaks.2015-10-02.nightly.log
+++ b/memleaks.2015-10-07.nightly.log
@@ -276,7 +276,6 @@ Number of leaked allocations
    1   24 UntypedField(complex(128))
    1   24 TypeAliasField(real(64))
    1   24 GenericClass(int(64))
-   2   16 local heap-converted data
    1   16 List(int(64))
    1   16 LocBlock(4,int(64))
    1   16 LocCyclic(2,int(64))
@@ -291,7 +290,7 @@ Total leaked memory (bytes)

Memory Leaks for examples Tests
```

Fix went in here
Lexical Improvements: Other Impacts

● Moves Chapel one step closer to being leak-free
  ● Users whose codes rely on begins will be much happier

● Revealed a ‘ugni’ network atomic limitation with stack vars
  ● Now fixed and included in the Cray module for 1.13
Lexical Improvements: Status and Next Steps

Status:
- Chapel now implements its lexical scoping rules better
- A historical source of memory leaks is now plugged

Next Steps:
- Implement checks to help protect users from ref-after-free issues
- Close remaining leaks, particularly arrays and domains
  - these have traditionally been reference counted, though not very well
  - and in distributed cases have been intentionally leaked in spite of ref counting
  - new semantics ought to reduce or eliminate need for reference counting
Evaluation of Current Memory Leaks
Memory Leaks: Background

● **Memory leak statistics are collected every night**
  ● Performance team reviews every week
  ● Currently gathering single locale leaks only

● **Two metrics are tracked:**
  1. Total bytes leaked
     ● Subject to test parameters (e.g., choice of array sizes)
  2. Number of tests with leaks
     ● Some tests run in multiple variations, so one oversight leads to many leaks

<table>
<thead>
<tr>
<th>Tests run</th>
<th>4,817</th>
</tr>
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<tbody>
<tr>
<td>Tests with leaks</td>
<td>1,073</td>
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<tr>
<td>Total memory allocated (MiB*)</td>
<td>31,614</td>
</tr>
<tr>
<td>Total memory leaked (MiB)</td>
<td>965</td>
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</tbody>
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April 11, 2016
* 1 KiB = 1024 bytes
Memory Leaks: Leaks by Byte

- Small number of tests dominate overall bytes leaked
  - Primarily due to distributed arrays

<table>
<thead>
<tr>
<th>Application</th>
<th>Tests</th>
<th>Leaked (MiB)</th>
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<th>Total %</th>
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<td>5.0</td>
<td>0.5</td>
<td>99.1</td>
</tr>
</tbody>
</table>
Memory Leaks: Distributed Arrays

● Another case of suffering from old lexical scoping rules
  ● Traditionally, feared freeing distributed arrays prematurely
    ● “what if some asynchronous task somewhere is still referring to it?”
  ● Unfortunately, we simply chose not to free them “for now”
    ● another case of “we’ll get to that later” (and again, “later is now!”)
    ● codes that use a fixed number of global distributed arrays get away with it
      ● many simple benchmarks are like this
      ● but clearly not acceptable in general / real applications

● As in preceding cases, new semantics help us greatly
  ● yet work remains to leverage them
  ● this is arguably our top priority for 1.14
## Memory Leaks: Leaks by Test Count

<table>
<thead>
<tr>
<th>Source</th>
<th>Count</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>User fails to reclaim memory</td>
<td>~400</td>
<td>37.3</td>
</tr>
<tr>
<td>Distributed arrays</td>
<td>~190</td>
<td>17.7</td>
</tr>
<tr>
<td>Sync/single</td>
<td>~155</td>
<td>14.4</td>
</tr>
<tr>
<td>Tuples of records</td>
<td>~100</td>
<td>9.3</td>
</tr>
<tr>
<td>Initialization of generic fields</td>
<td>~80</td>
<td>7.5</td>
</tr>
<tr>
<td>Field initializer</td>
<td>~40</td>
<td>3.7</td>
</tr>
<tr>
<td>First-class functions</td>
<td>~25</td>
<td>2.3</td>
</tr>
<tr>
<td>main(args : [] string)</td>
<td>~20</td>
<td>1.9</td>
</tr>
<tr>
<td>Runtime types</td>
<td>~15</td>
<td>1.4</td>
</tr>
<tr>
<td>Misc and further classification required</td>
<td>~50</td>
<td>4.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,073</strong></td>
<td></td>
</tr>
</tbody>
</table>
Memory Leaks: User fails to reclaim (37.3%)

- Many simple tests leak classes/buffers in trivial ways

```cpp
class C {
    var x : int;
}

var c = new C(1);

writeln(c);

// No delete for c, so it leaks
```

- Leak-freedom was not the original point of the test
- Generally easy to resolve
  - In a few cases, removing the leak could change the intent of the test
Memory Leaks: Distributed arrays (17.7%)

- Driven by original language semantics
  - Arrays could outlive lexical scopes due to asynchronous tasks

- Semantics now revised, but implementation work required
  - Continue to refine record implementation
  - Improvements to constructor/destructor semantics
Memory Leaks: Sync/Single (14.4%)

- **Driven by original language semantics**
  - Syncs/singles could outlive lexical scopes due to asynchronous tasks
    - similar to array case
  - Semantics now revised, but implementation has not been updated

- **Syncs/singles currently implemented as a class**
  - However, user is not expected to delete syncs/singles
  - We intend to revise the implementation
    - Likely by conversion to a record-wrapped class

- **Most sync/single leaks are due to use of ‘Random’ module**
  - Each instance of a RandomStream stores a synchronization variable
  - More than 120 of the 155 sync leaks are due to this module
  - Intend to modify the internal implementation to delete for now
    - revert once sync is leak-free
Memory Leaks: Tuples of records (9.3%)

```javascript
const (dist, ) = (new dmap(new DefaultDist()), );
```

- **Leaks tuple components when at the module level**
  - Missing an autoDestroy during tuple construction
  - Reference count is off-by-one on the distribution

- **Does not leak components when at the procedure level**
  - Required autoDestroy is included

- **Nearly 100 tests share a single module with this pattern**
Memory Leaks: Initialize Generic Field (7.5%)

- All uses of a sparse subdomain leak

\[
\begin{align*}
\text{var } & \text{ D1 : domain (1) } = \{ 1 \ldots 10 \}; \\
\text{var } & \text{ DS1 : sparse subdomain (D1); }
\end{align*}
\]

- D1 is captured by DS1 and is not released correctly
- DefaultSparseDom has a generic field

\[
\begin{align*}
\text{class } & \text{ DefaultSparseDom : BaseSparseDom } \{ \\
& \text{param } \text{ rank : int; } \\
& \text{type } \text{ idxType; } \\
& \text{var } \text{ parentDom; } \\
& \ldots
\end{align*}
\]

- An error in the compiler-generated default constructor
- The parentDom field is “initialized” from D1 twice
- Reference count is off-by-one
- Any class/record with this pattern will leak
Memory Leaks: Field Initializers (3.7%)

● An array `temp` is created for this field initializer:

```plaintext
class foo {
    var i : [1 .. 5] int = [ 1, 2, 3, 4, 5 ];
}
```

● A low-level operator disables the call to `autoDestroy`
  ● Leaks any object that requires memory management
  ● Leaks for the field initialization in classes and records

● The following does not leak:

```plaintext
class foo {
    var i : [ 1 .. 5] int;

    proc foo() { i = [ 1, 2, 3, 4, 5 ]; } }
```
Memory Leaks: Runtime types (1.4%)

- Some types must be explicitly represented at run-time:

```c
const Ndom : domain(1) = { 1 .. 10 };

type Ntype          = [Ndom] int;
```

- `Ntype` stores a reference to `Ndom`
  - Reference count for `Ndom` is incremented while initializing `Ntype`
  - No call to free `Ntype` at end of scope
  - Reference count for `Ndom` is not decremented
- `Ndom` is leaked
Memory Leaks: Status and Next Steps

**Status:** Remaining leaks driven by a few well-defined modes

- Distributed arrays are a large and known problem
  - Dominates metric for leaks by bytes
  - Revision to language semantics a key to resolving this
- Many tests inattentive to memory management
  - Dominates metric for count of tests that leak
  - Fixing these cases is housecleaning
- A modest number of other patterns

**Next Steps:** Drive leak metrics to zero for 1.14 release

- Would signal increasing maturity of the implementation
- Extend testing framework to highlight leak regressions
  - Avoid new compiler-based errors
  - Ensure new tests are clean (when practical)
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