Benchmarks, Performance Optimizations, and Memory Leaks

Chapel Team, Cray Inc.

Chapel version 1.13

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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

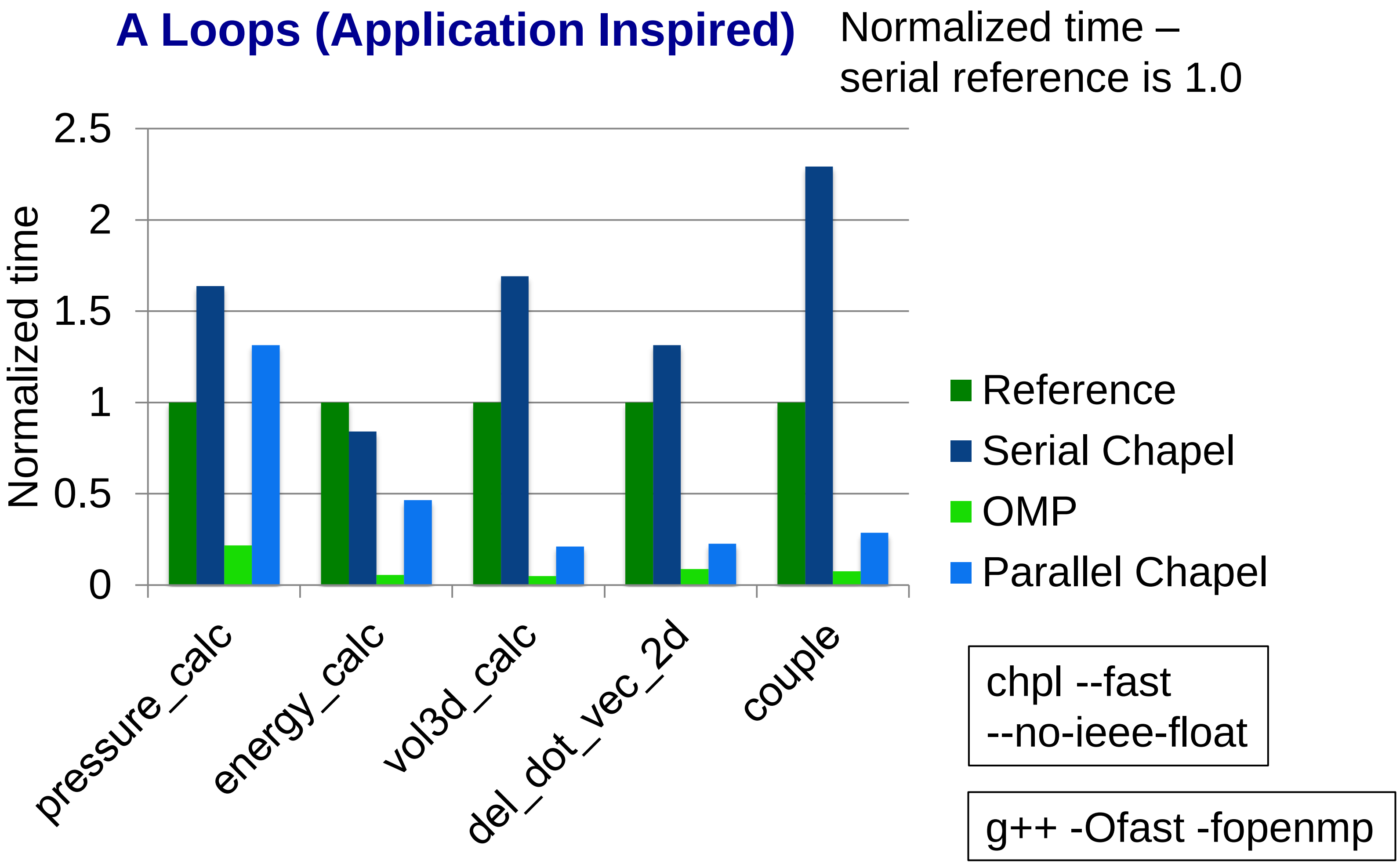
LCALS Code
Richard D. Hornung
LCALS version 1.0
LLNL-CODE-638939
2013

- **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.

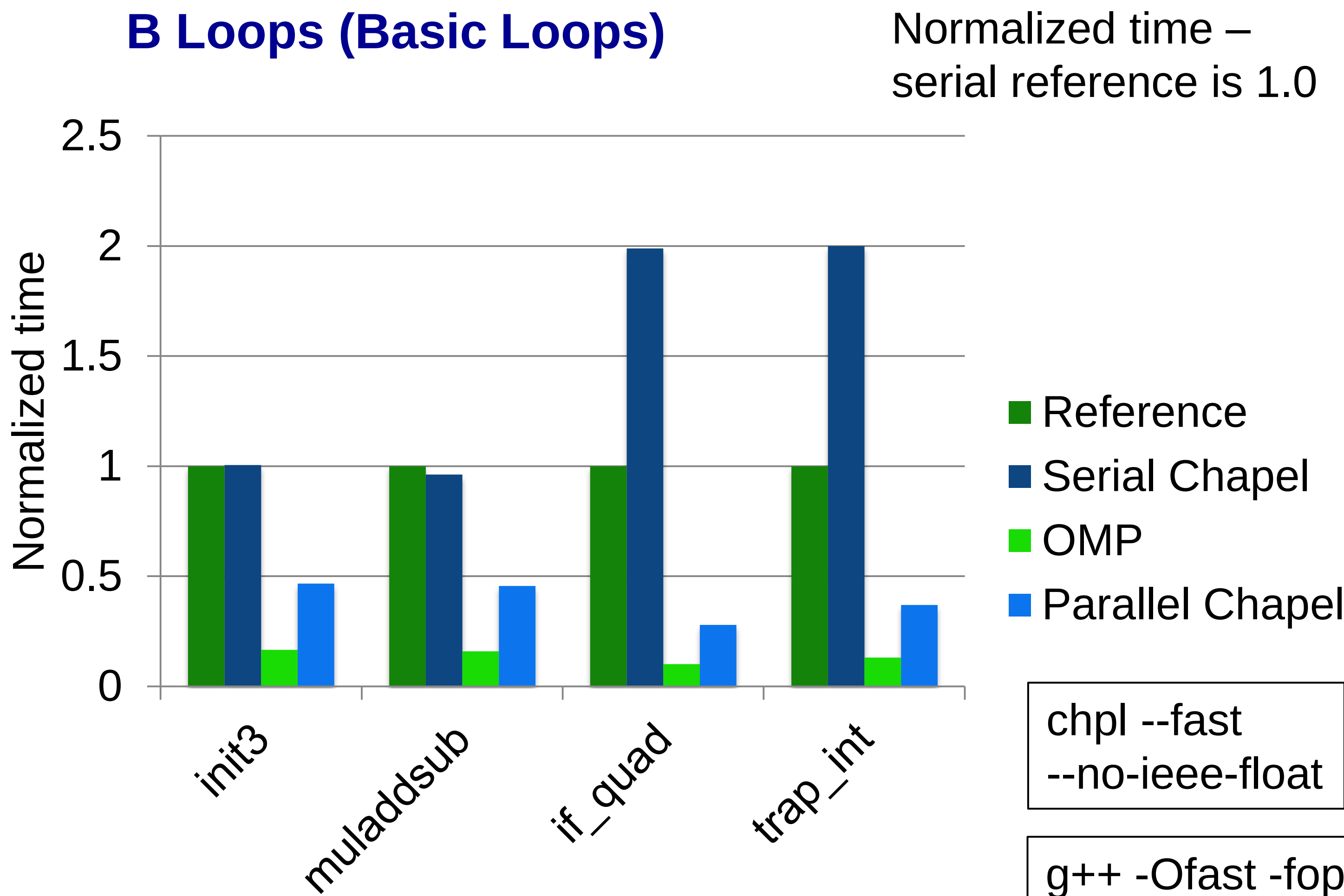
LCALS: This Effort

- **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



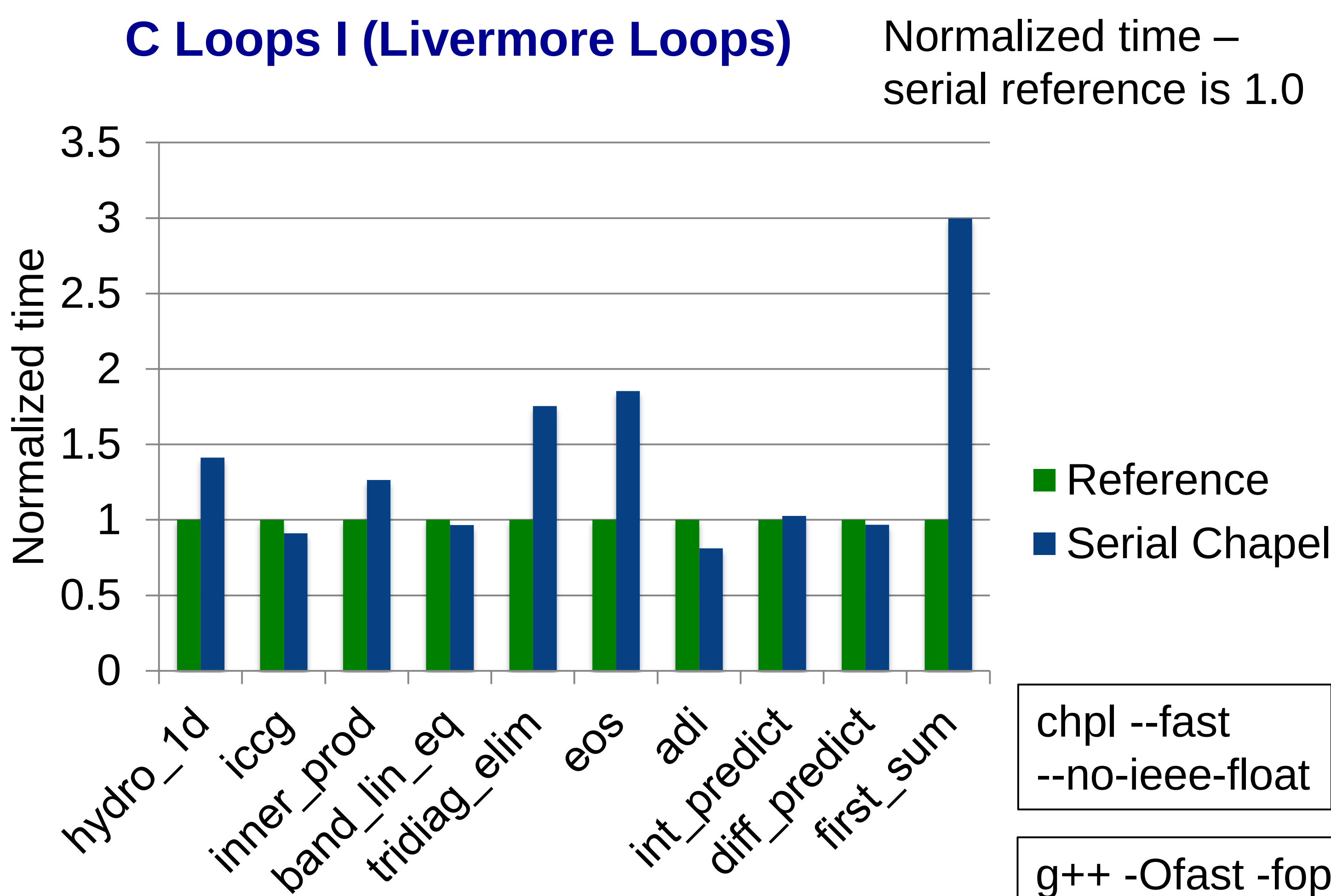
LCALS: Performance Comparison



chpl --fast
--no-ieee-float

g++ -Ofast -fopenmp

LCALS: Performance Comparison

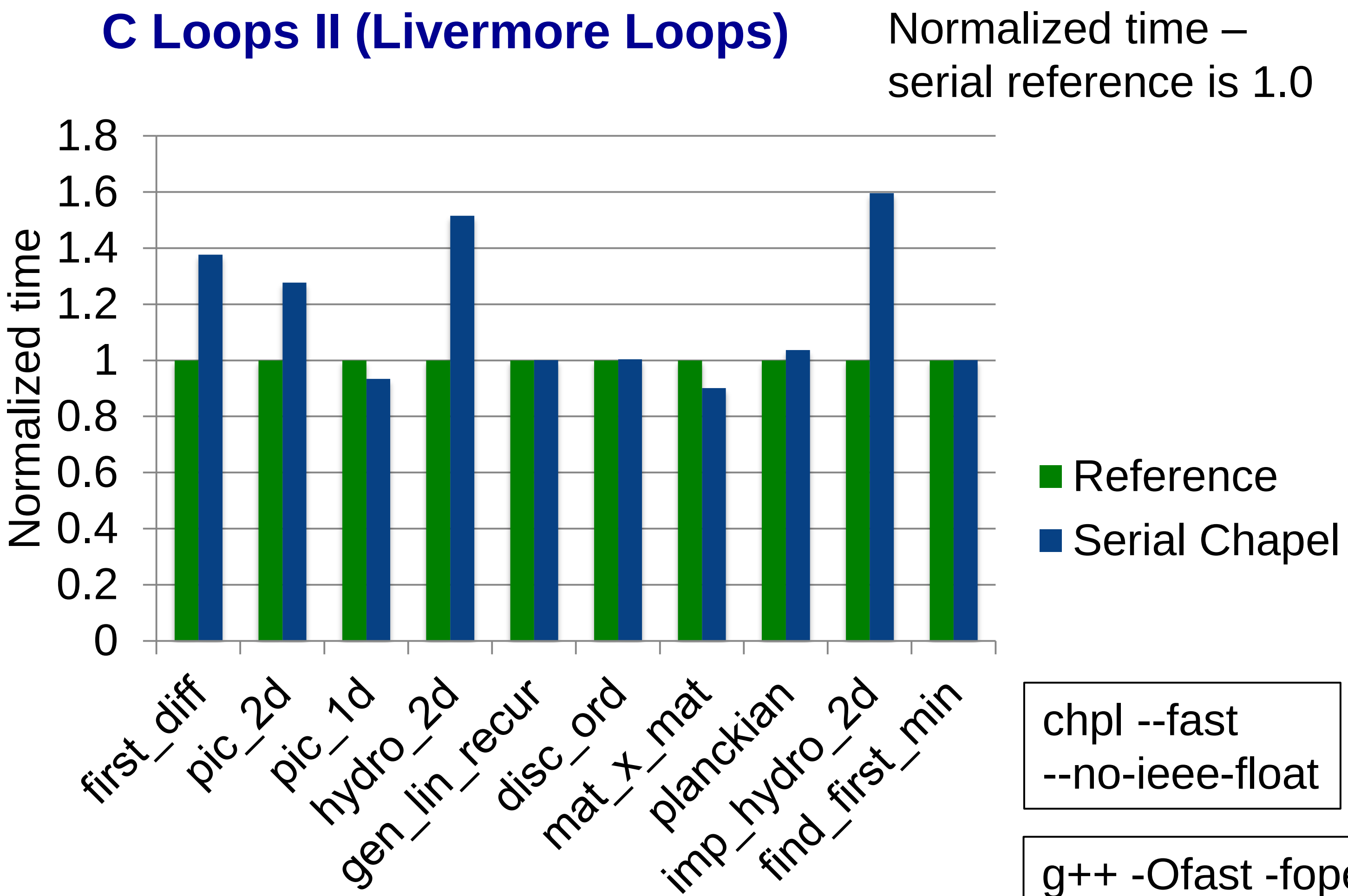


Normalized time – serial reference is 1.0

chpl --fast --no-ieee-float

g++ -Ofast -fopenmp

LCALS: Performance Comparison



Normalized time – serial reference is 1.0

chpl --fast
--no-ieee-float

g++ -Ofast -fopenmp

LCALS: Status

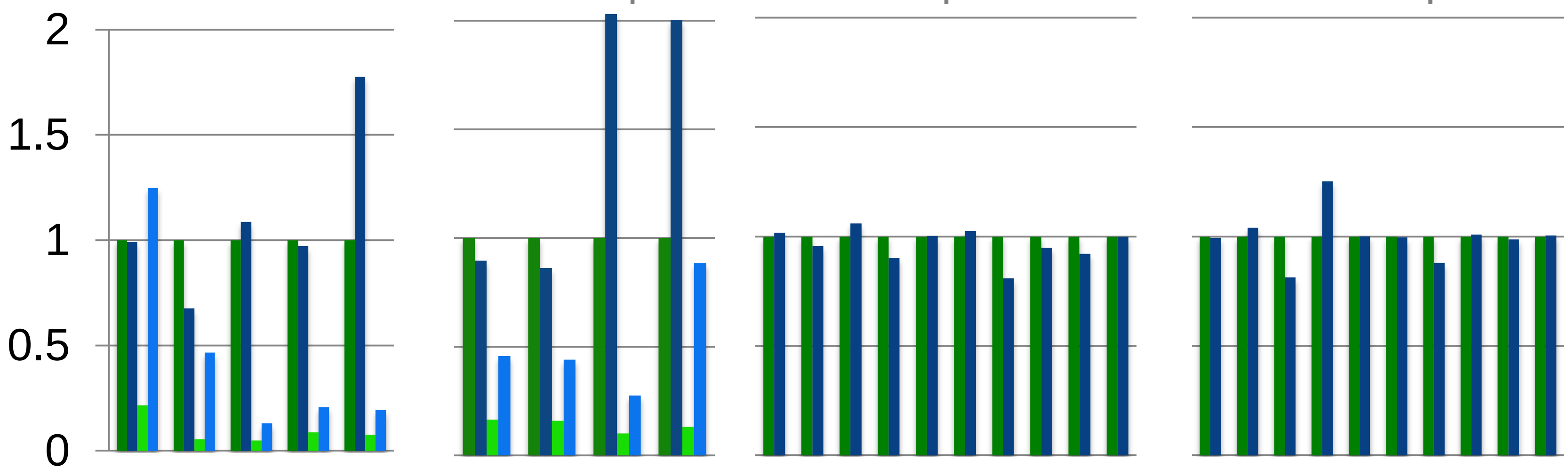
- **RAW and RAW+OMP kernels ported**
- **Performance is hit-or-miss**
  - serial performance:
    - ~half of the serial kernels are competitive with the reference versions
    - a handful are >2x off (e.g. first_sum, couple, …)
    - the remainder need some attention
  - parallel performance:
    - generally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

  http://chapel.sourceforge.net/perf/chapcs/?graphs=lcalsshort,lcalsmedium,lcalslong
- **Chapel LCALS port included in the 1.13 release**

  `$CHPL_HOME/examples/benchmarks/lcals`

LCALS: Array Inner Multiplications

- **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:
    $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

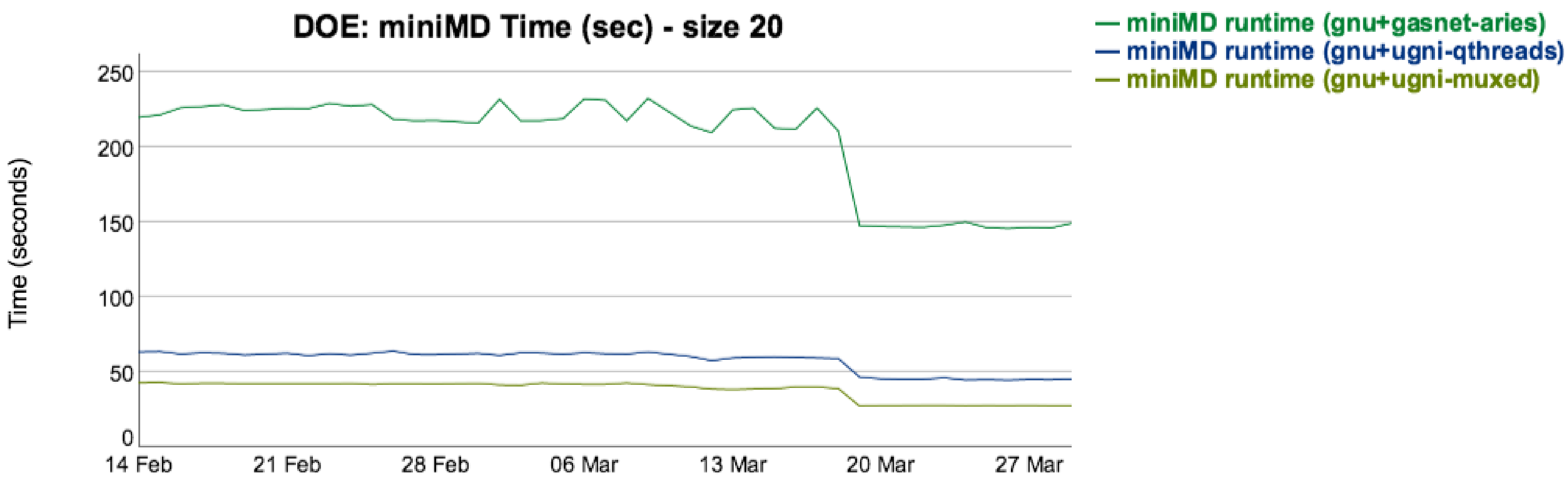
MiniMD: Performance Improvements

- **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

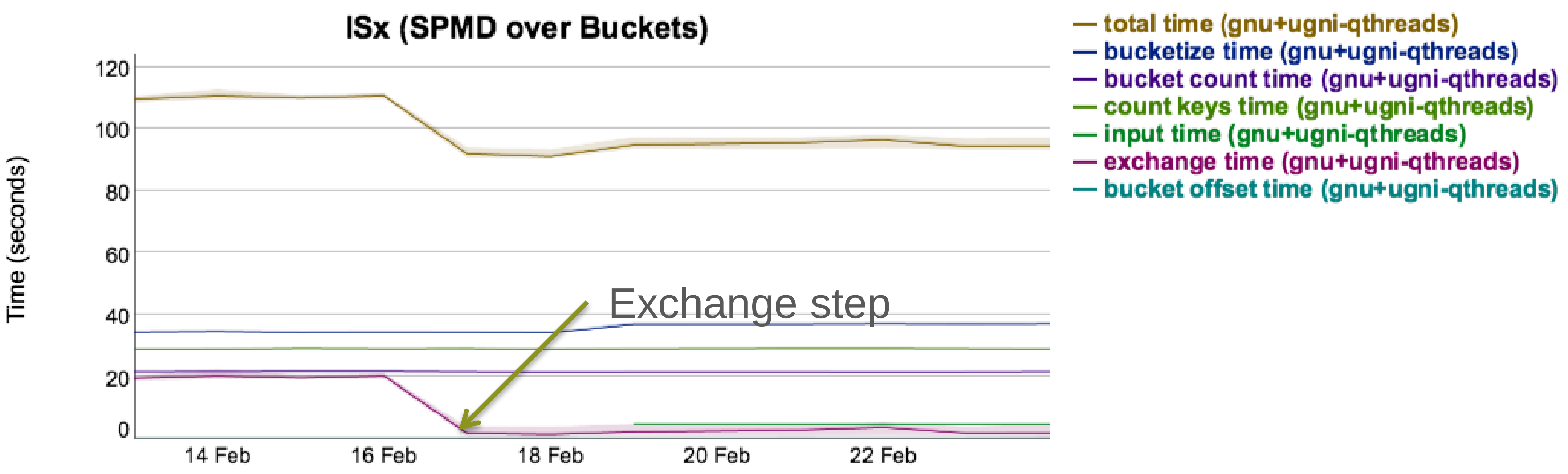
- **A good case study for Chapel**
  - a common parallel pattern for distributed memory programming

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

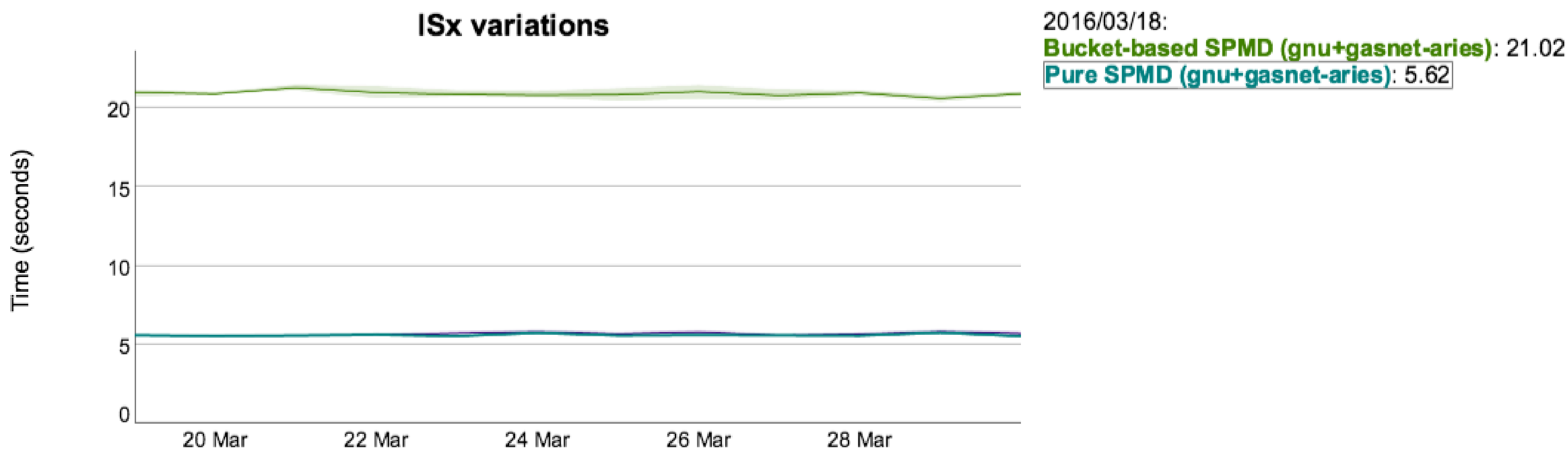
ISx: Performance – Bulk Transfer

- **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

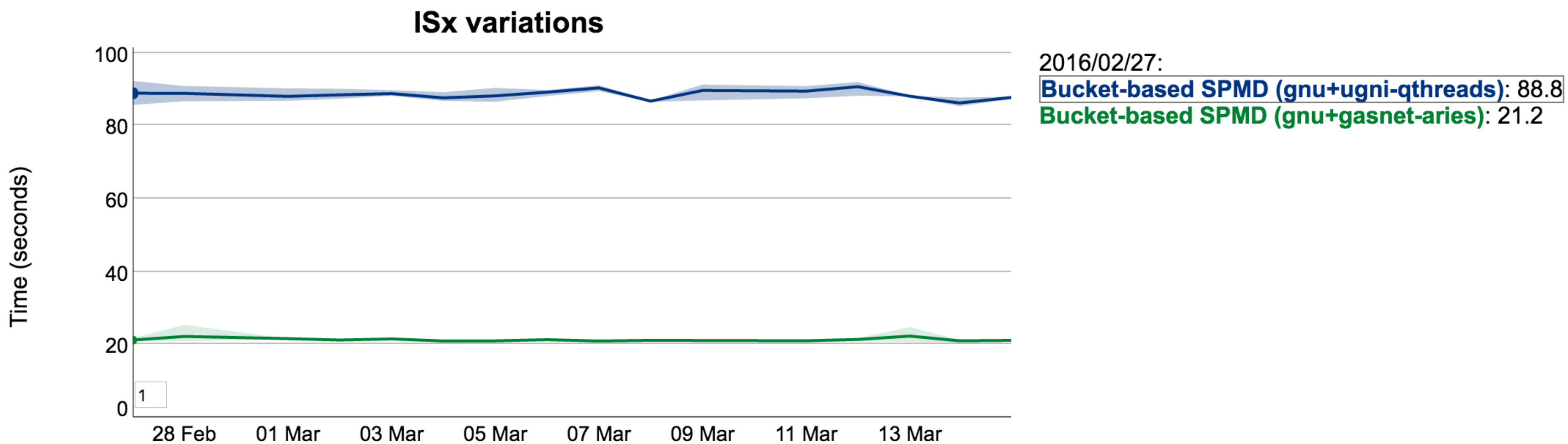
- **Global-view Chapel is slower than the SPMD variation**
  - by up to 4x!



- **Likely due to atomics**
  - Global-view uses atomics to coordinate between forall-loop iterations
  - SPMD uses serial for loops without atomics

ISx: Performance – Proc. vs. Network 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

ISx: Performance – Loop-Invariant Expressions

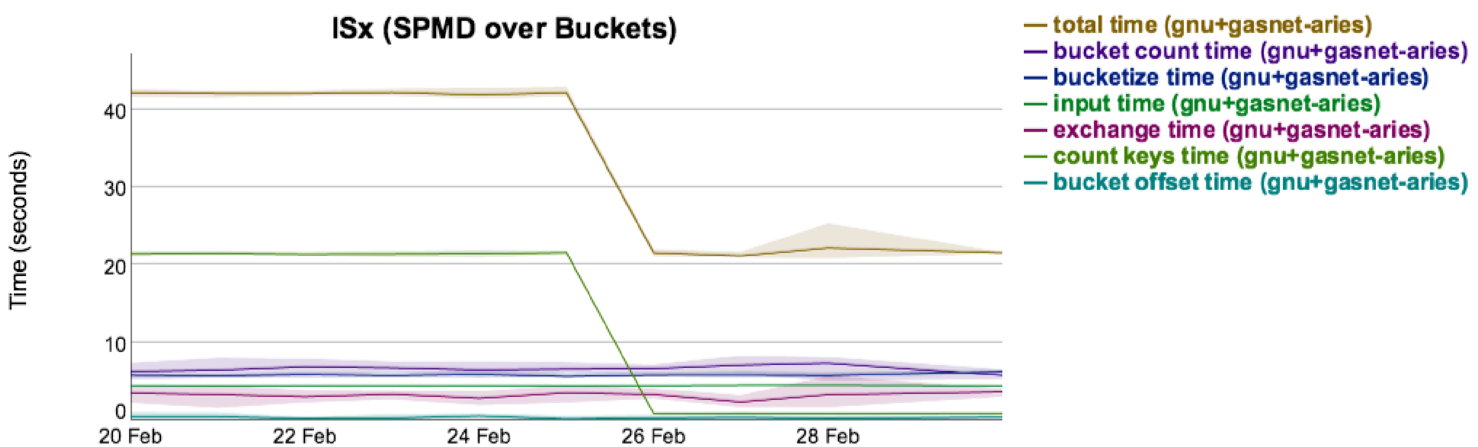
- **Manually optimized user-level code:**
  - Many loops contain loop-invariant common sub-expressions

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

  - Manually hoisting such expressions had a huge impact

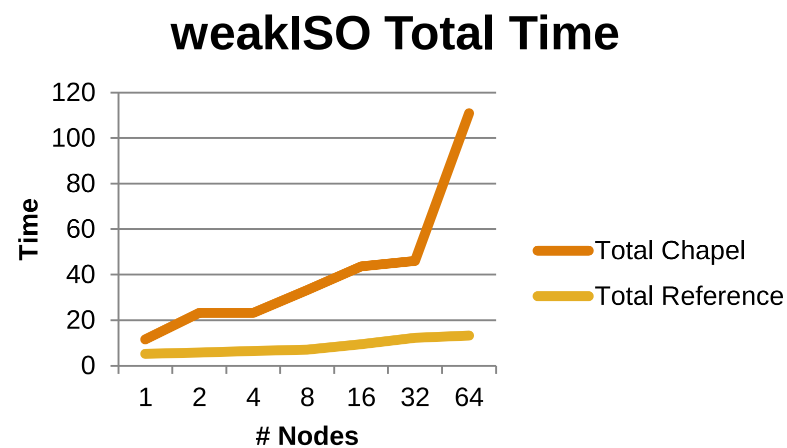
```
ref myBucket = allBucketKeys[taskID];
for i in 0..#myBucketSize do
  myLocalKeyCounts[myBucket[i]] += 1;
```

  - Compiler should automatically hoist such sub-expressions

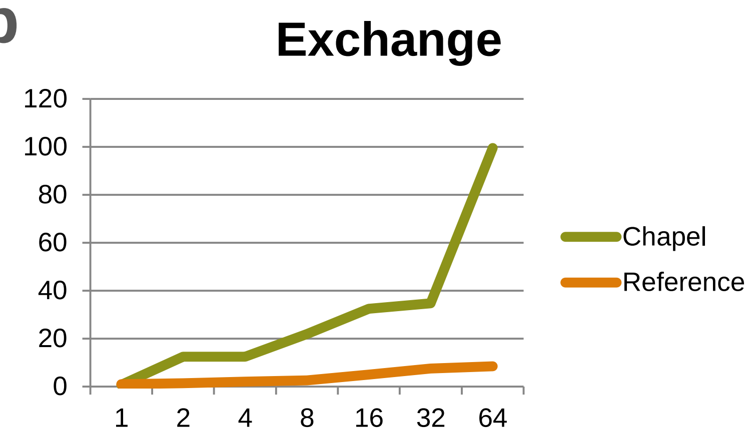


ISx: Performance Summary

- **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):

```
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:

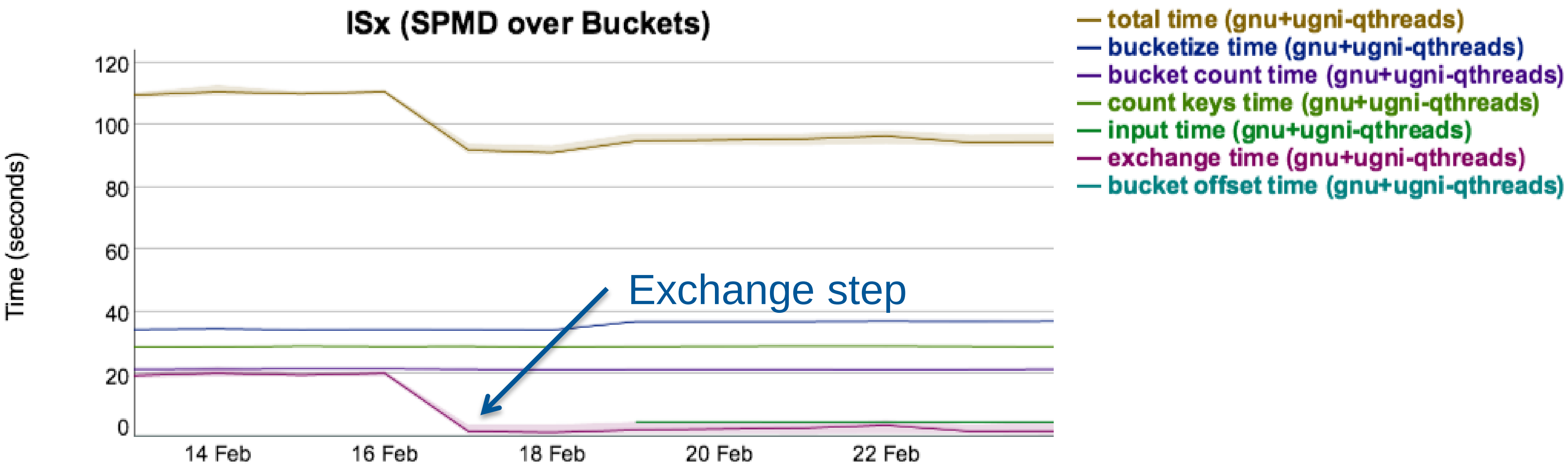
```
var A, B : [1..20] int;

// 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);
}
```

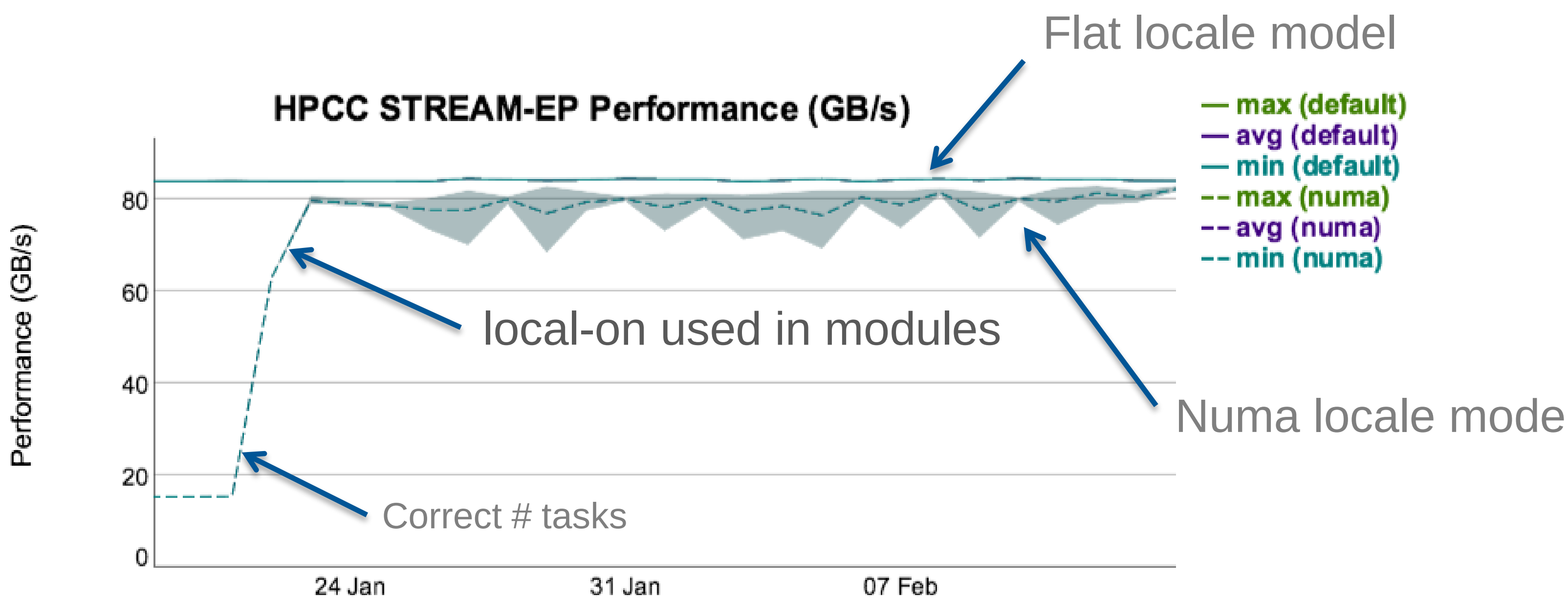
- Generate runtime error if ‘local on’ leaves current node
  - checks can be disabled by --no-local-checks, --no-checks, or –fast

// 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



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:

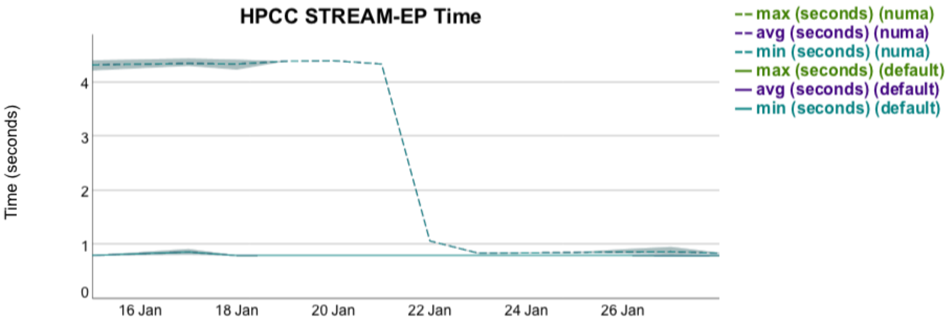
- Numa locale model set top-level *here.maxTaskPar* incorrectly
  - used *numSublocales* instead of runtime *chpl_task_maxTaskPar()*
  - e.g., for two 12-core processors, *maxTaskPar* was 2 instead of 24
- Forall loops create parallelism based on top-level *maxTaskPar*
  - so, *maxTaskPar*=2 resulted 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'

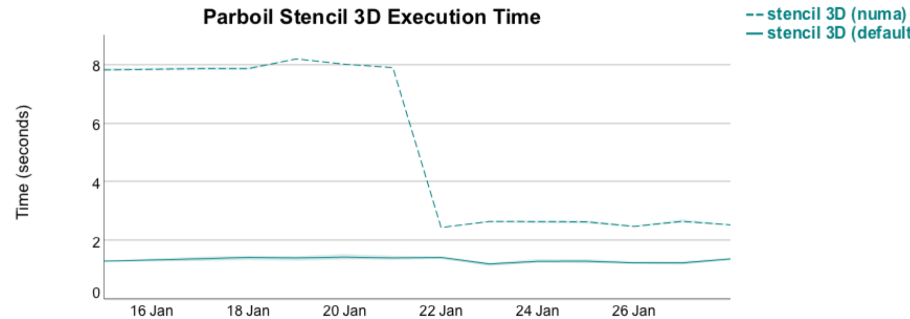
This Effort:

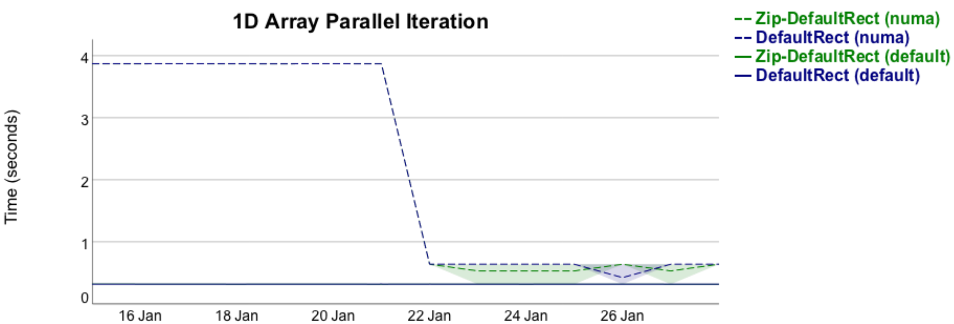
- Set top-level *here.maxTaskPar* correctly
  - improved stream performance using 'numa' locale model to 63 GB/s

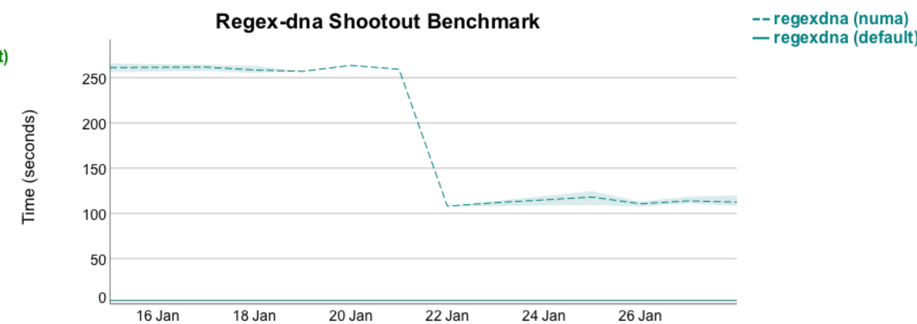
Numa maxTaskPar: Impact

- Resulted in dramatic performance improvements









Array-as-Vector Improvements

Array-as-Vector: Background and This Effort

Background:

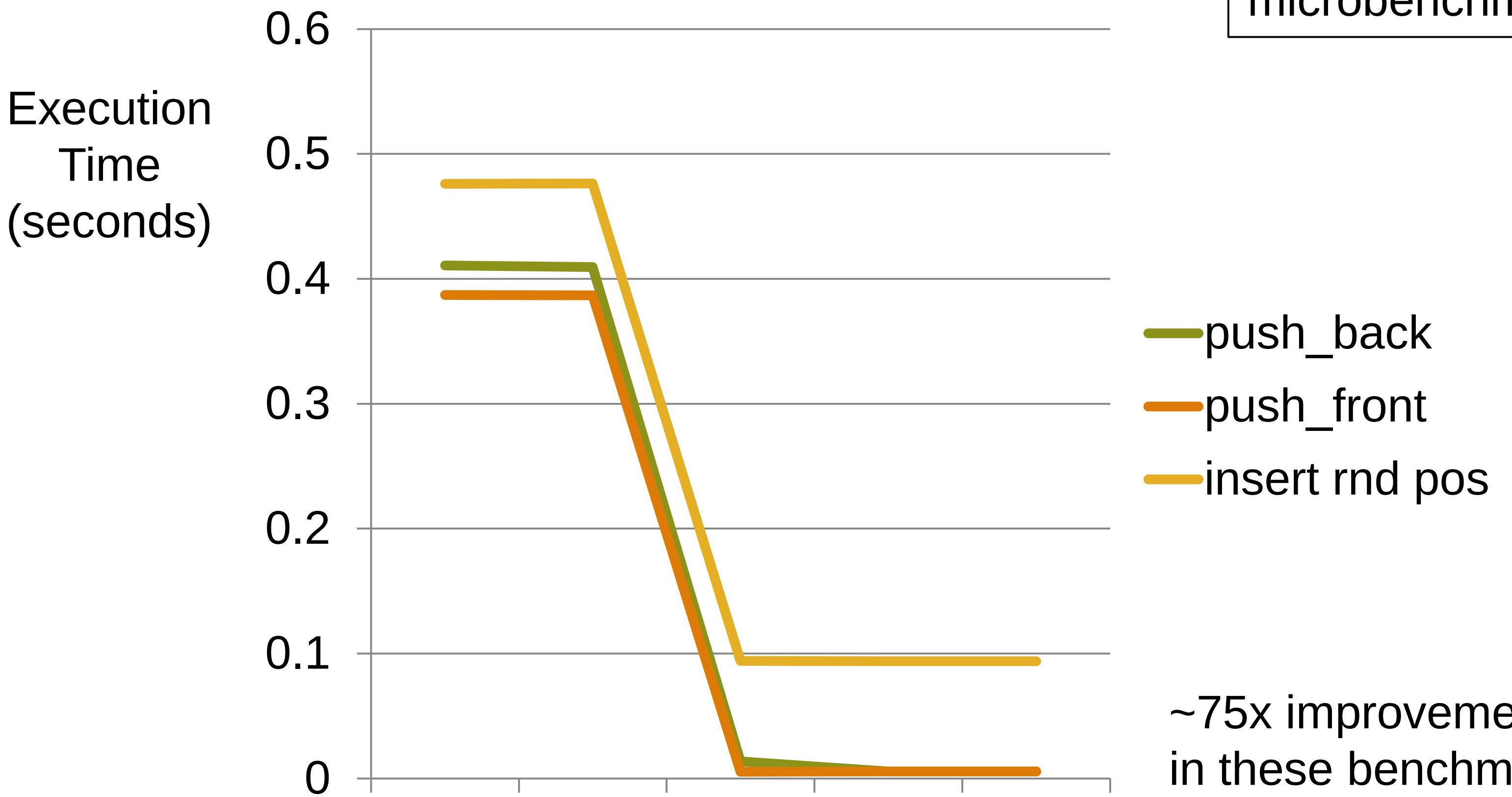
- Vector operations on arrays were added in 1.10
  - A.push_back(val)
  - A.insert(pos, val)
  - A.pop_front()
  - etc.
- Each insertion or deletion triggered an array reallocation
  - Never wasted any space
  - But *very* slow!
  - (goal at that time was to get feature up and running, tune later)

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

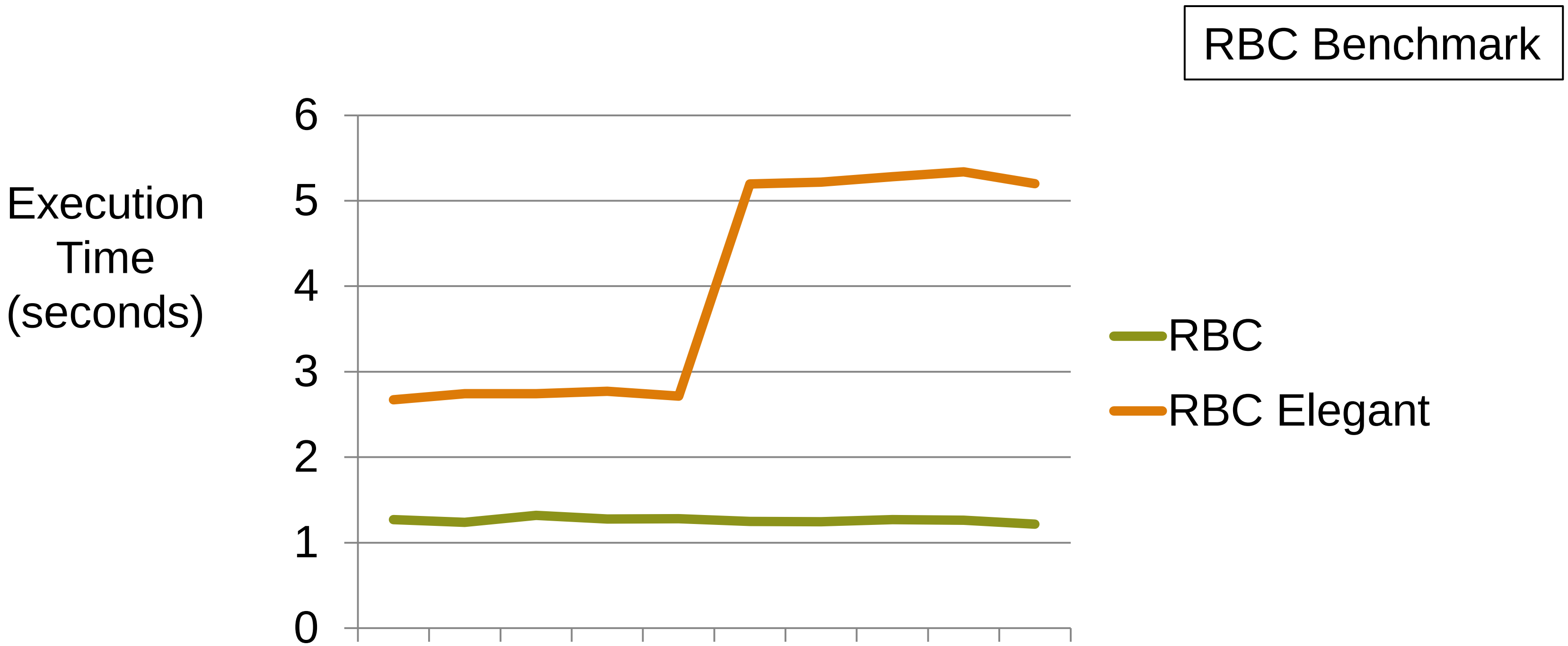
Array-as-Vector: Impact

Array-as-vec microbenchmarks



~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

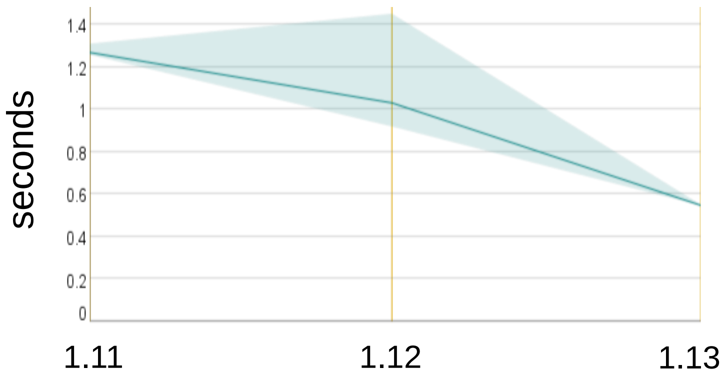
This Effort: Implement reductions using forall loops

- 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

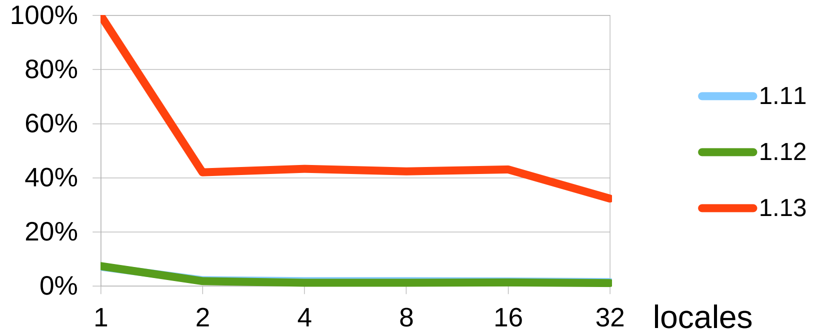
Reduction Performance: Impact – *Reduction*

Benchmark: a single plus-reduction over a large array

single-locale time



multi-locale efficiency
vs. 1.13 on 1 locale (0.307s)



- 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

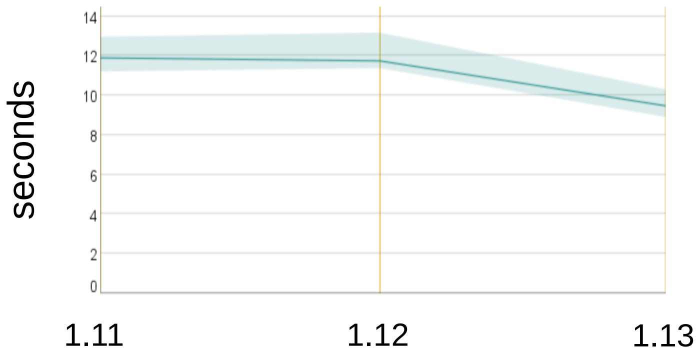
- uses weak scaling
  (constant array size per locale)
- 1.12 to 1.13 speedup: 13x to 30x
- 1.11 is comparable to 1.12
  (overlaps on graph)
- measured on Cray XC40

Reduction Performance: Impact – CG

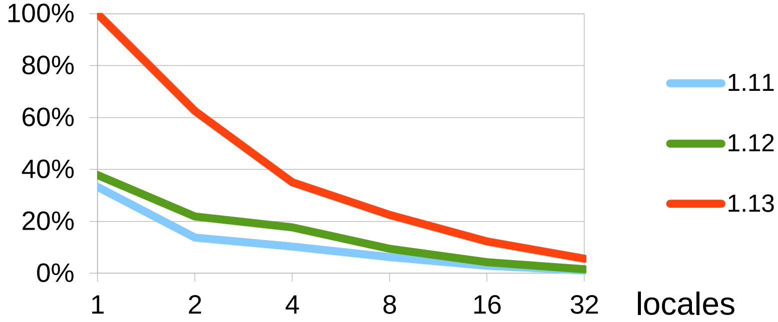
Benchmark: an iterative conjugate gradient benchmark

- earlier evaluation presented by Laura Brown at CHIUW 2015

single-locale time



multi-locale efficiency
vs. 1.13 on 1 locale (17.16s)



- 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

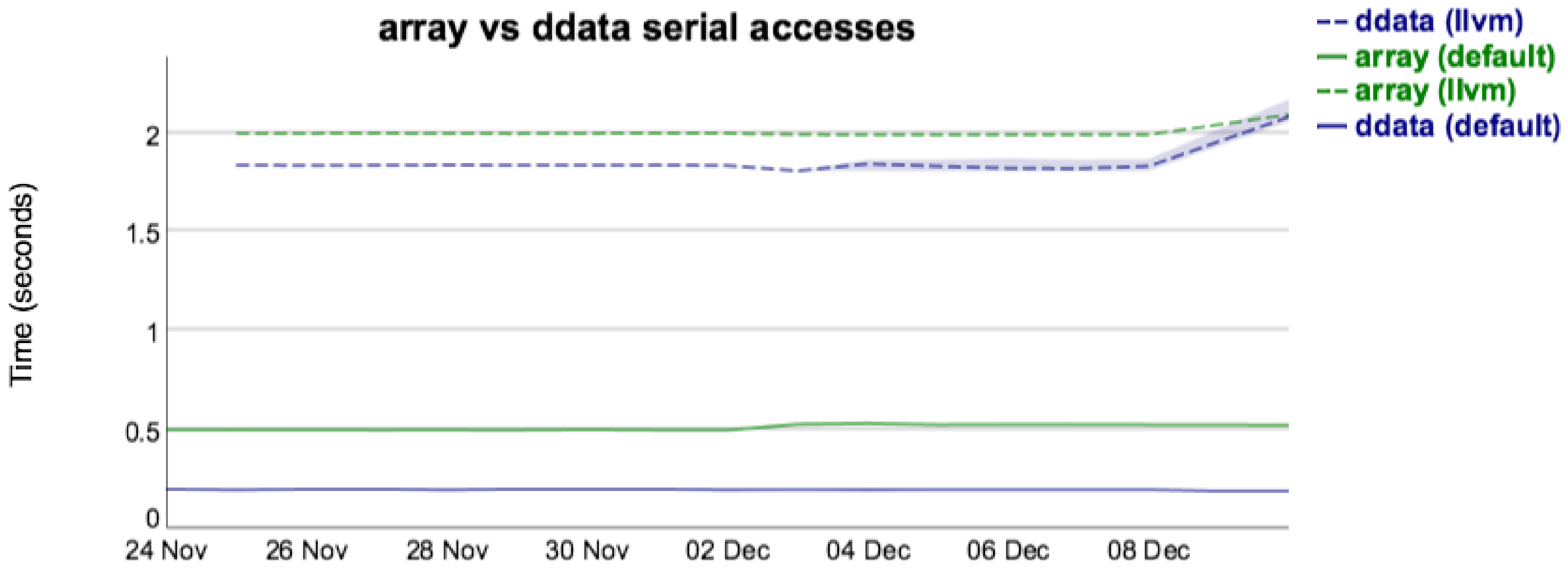
Reduction Performance: Next Steps

- **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

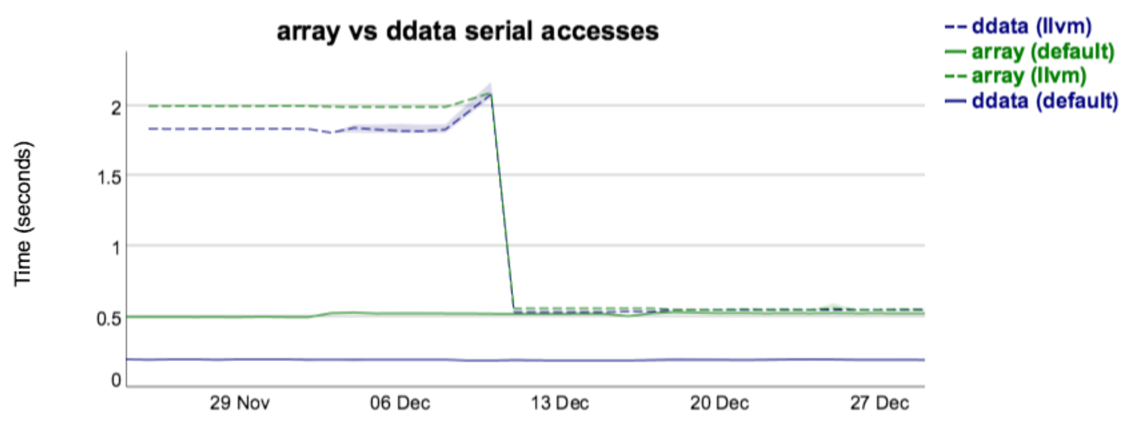
- **Noticed significant performance gaps with --llvm back-end**
  - especially for microbenchmarks
- **e.g., array performance test was about 9x slower**



- **Started regular perf. testing to help investigate the issue**

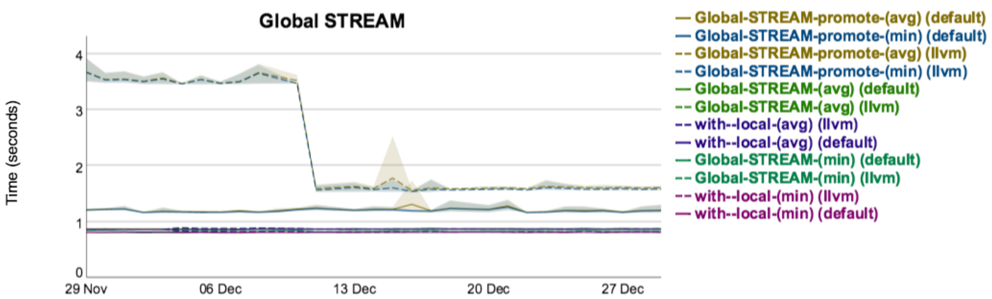
LLVM Performance: This Effort

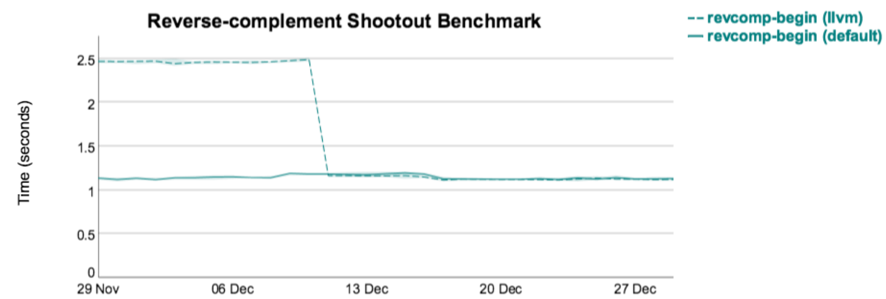
- With --llvm, *link* step actually does target code generation
- Link step was missing optimization flags
- Simply adding these flags addressed the performance gap

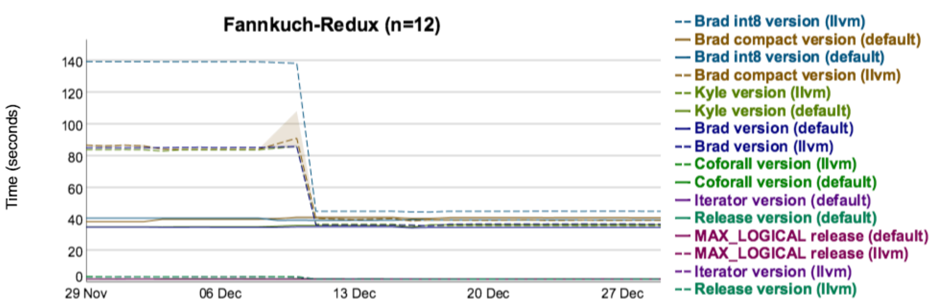


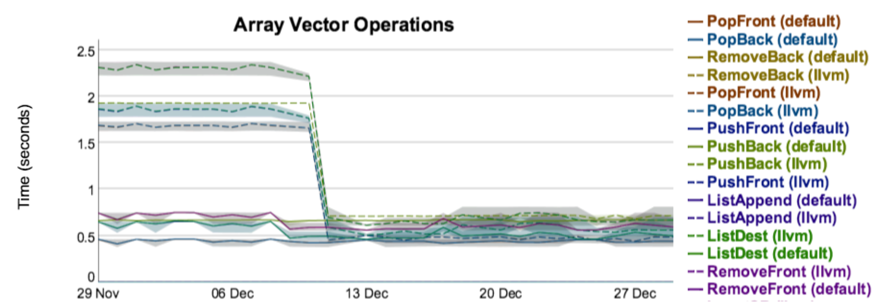
LLVM Performance: Impact

- Saw significant performance improvements



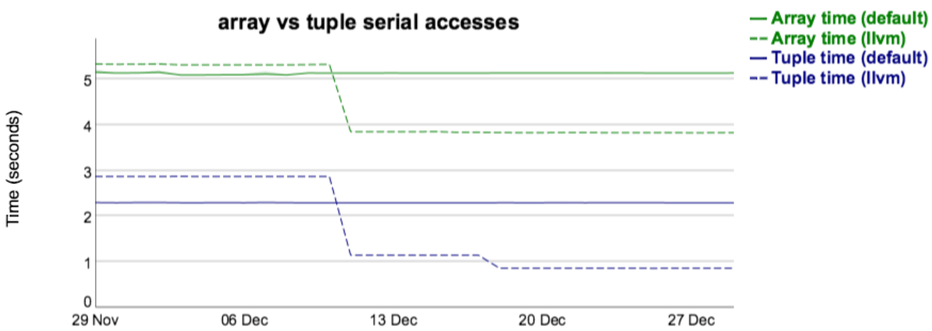


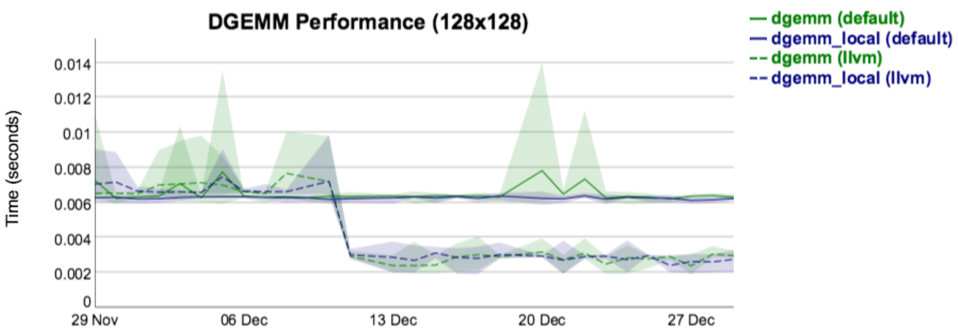


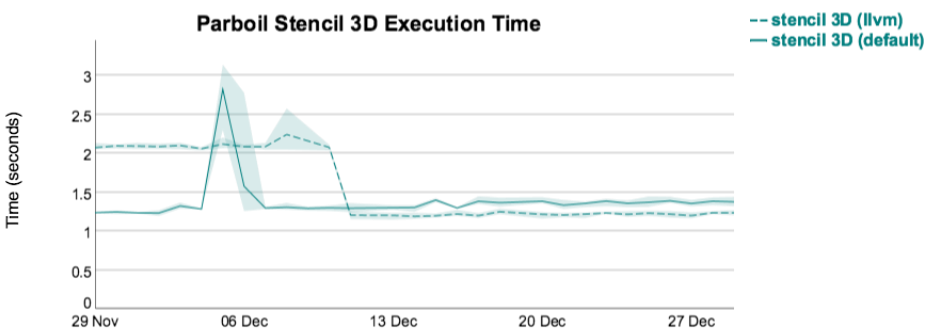


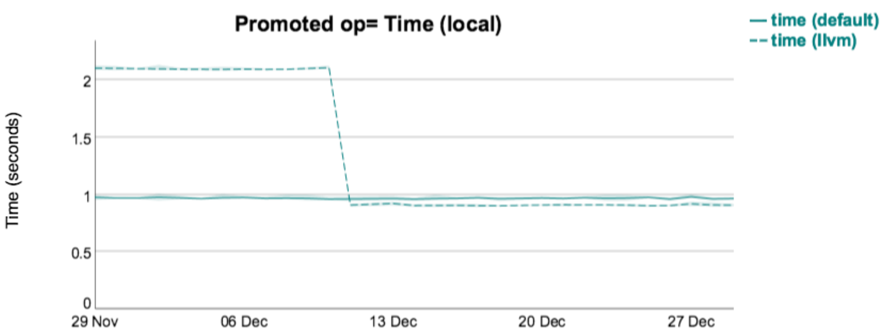
LLVM Performance: Impact

- 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**

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

previous generated code:

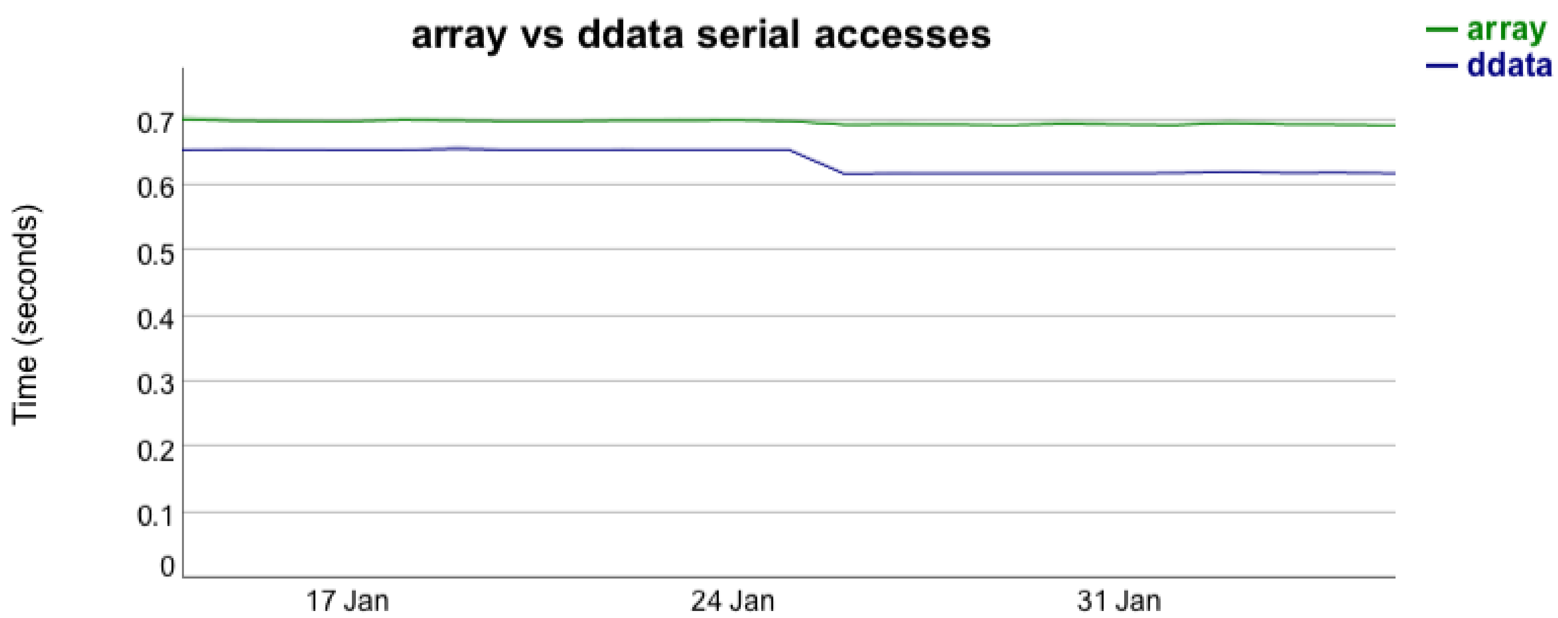
```
chpl_build_low_bounded_range(INT64(0), &call_tmp_l); // simple constructor
chpl___POUND(&call_tmp_l, INT64(10), &call_tmp_b);   // ~10 branches
low = (&call_tmp_b)->_low;
end = (&call_tmp_b)->_high;
for (i = low; i <= end; i += INT64(1))
  writeln(i);
```

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

```
{
  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:

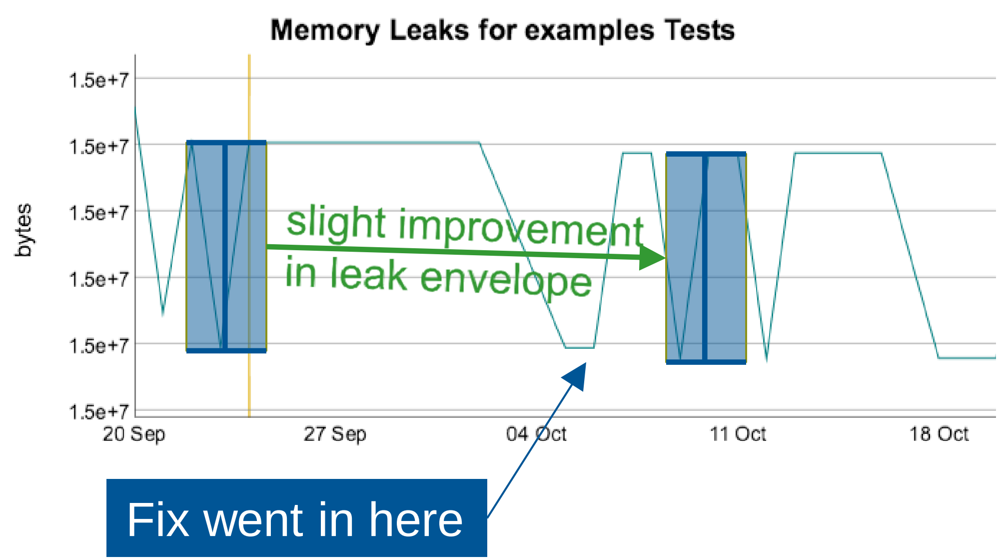
- Tighten up such cases
  - Stop allocating stack variables on the heap due to ‘begin’ statements

```
{
  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
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)
 ==========================================================
```



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

Tests run	4,817
Tests with leaks	1,073
Total memory allocated (MiB*)	31,614
Total memory leaked (MiB)	965

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

Application	Tests	Leaked (MiB)	Fraction %	Total %
studies/hpcc/PTRANS	1	805.1	81.5	81.5
optimizations/bulkcomm	8	55.7	5.6	87.1
studies/hpcc/HPL	3	39.2	4.0	91.1
users/aroonshama	8	27.9	2.8	93.9
studies/amr	2	18.7	1.9	95.8
benchmarks/ssca2	5	13.9	1.4	97.2
lammps/shemmy	1	6.9	0.7	97.9
studies/ssca2	5	6.1	0.7	98.6
benchmarks/miniMD	1	5.0	0.5	99.1

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

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

Memory Leaks: User fails to reclaim (37.3%)

- **Many simple tests leak classes/buffers in trivial ways**

```
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%)

```
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**

```
var D1  : domain(1) = { 1 .. 10 };
var DS1 : sparse subdomain(D1);
```

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

```
class DefaultSparseDom : BaseSparseDom {
  param rank : int;
  type  idxType;
  var   parentDom;
  …
```

    - 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:**

```
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:**

```
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:**

```
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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