Performance Optimizations

Chapel Team, Cray Inc.

Chapel version 1.14

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Outline

- **Array Optimizations**
  - Array Indexing Optimization
  - Promoted Fast Followers Improvements
  - Strided Bulk Transfer
  - Array-as-vec Improvements
- **Locality Optimizations**
  - Wide Pointer Analysis Improvements
  - Reducing Task Counting Overhead
  - Local On Statements Optimization
- **Qthreads Improvements**
  - Native Qthread Sync Vars
    - Reduction Lock Improvements
  - Qthreads “Distrib” Scheduler
- **Runtime Optimizations**
  - Jemalloc Changes
  - Faster Complex .re/.im
- **Other Performance Optimizations**

Array Optimizations

Array Indexing Optimization

Array Indexing Opt: Background

- **Chapel arrays are significantly richer than C/C++ arrays**
  - first-class language concept with support for:
    - non-0 based indexing, slicing, rank changing, and much more

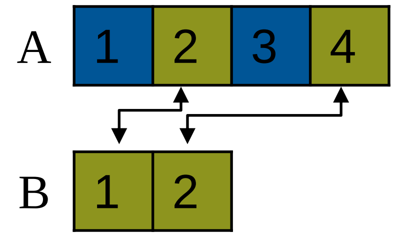
- **Historically, these features had a performance cost**
  - previous optimizations have lessened much of the performance cost
    - shifted base pointer optimization, loop invariant code motion, etc.

- **A remaining cause of overhead was a multiply for indexing**
  - multiply is only needed for some specific/rare use-cases
    - rank-change, re-indexing, strided slice aliases
  - but all arrays were paying the price

Array Indexing Opt: Background

- **For example, multiply needed for a strided slice alias**

```
var A: [1..4] int;
var B: [1..2] => A[2..4 by 2];
```



- B is an alias to a subset of A (B is a "view" into A's data)
  - logically, accesses of B are translated to accesses of A

indexing is translated with a "blk" offset

`B[2]` => A[2 * blk] => A[2 * 2]

previously, multiply occurred for all arrays

`A[2]` => A[2 * blk] => A[2 * 1]

Array Indexing Opt: This Effort

- **“Array Views” will remove multiply in a principled manner**
  - but that work wasn’t completed in time for 1.14

- **Added a simple compiler optimization in the interim**
  - removes inner multiply, when it can prove no array needs it
    - i.e. if even one array requires it, all arrays will have the inner multiply
    - unfortunate, but few programs require it, and it’s better than the status quo

Array Indexing Opt: Impact

- **Now generating ideal 1D array indexing code**

```
for i in 1..10 do
  A[i] = i;
```

Used to generate

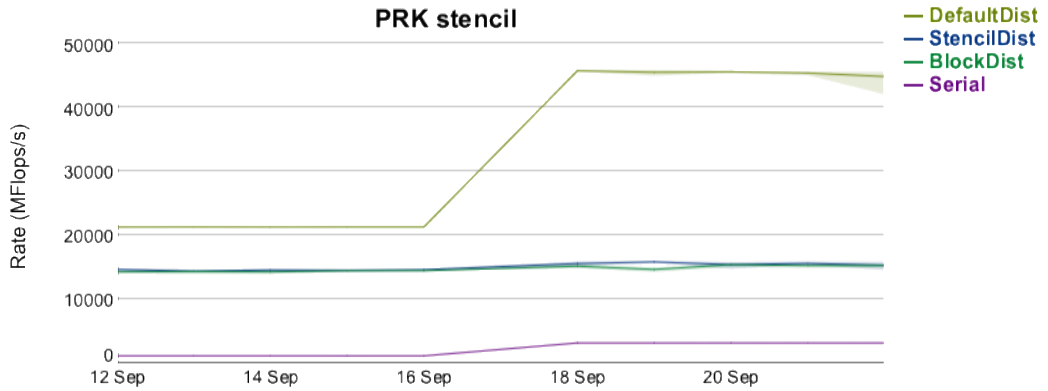
```
for (i = INT64(1); i <= INT64(10); i += INT64(1)) {
  index = INT64(0);
  rank1_index = (i * blk);    // blk was always 1
  index += rank1_index;
  elem_ptr = (arr_base + index);
  *(elem_ptr) = i;
}
```

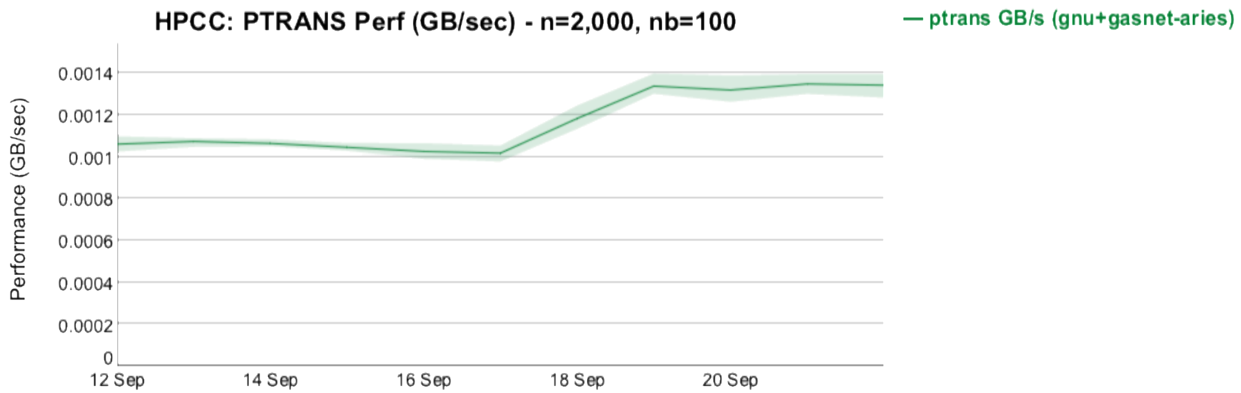
Now generates

```
for (i = INT64(1); i <= INT64(10); i += INT64(1))
  *(arr_base + i) = i;  // identical to arr_base[i] = i;
```

Array Indexing Opt: Impact

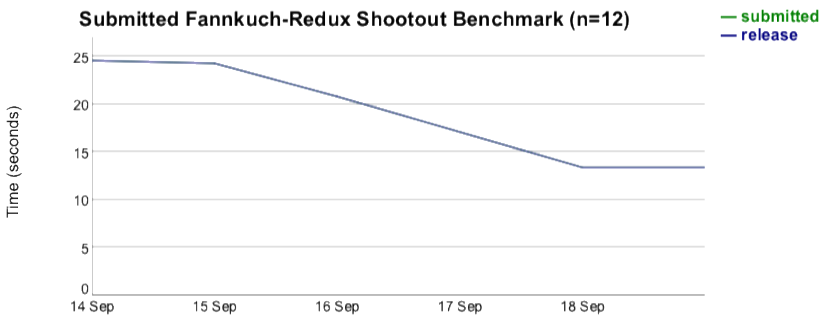
- **Saw significant performance improvements**
  - particularly for array-heavy benchmarks (higher is better)

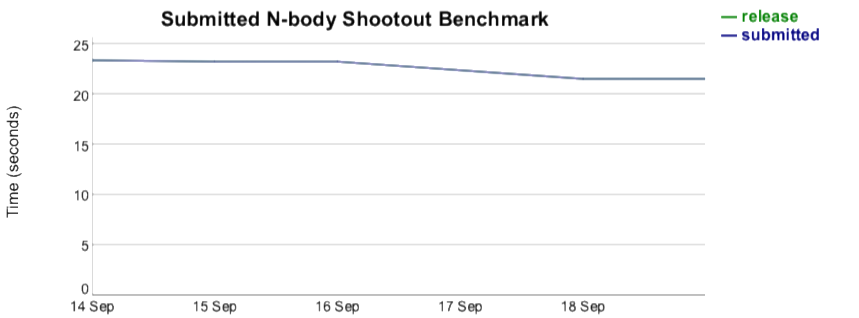


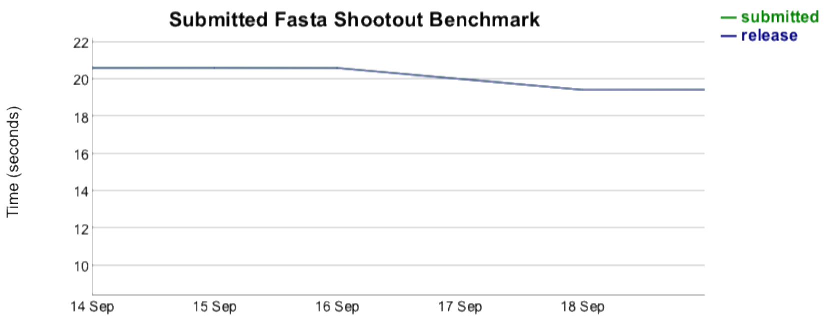


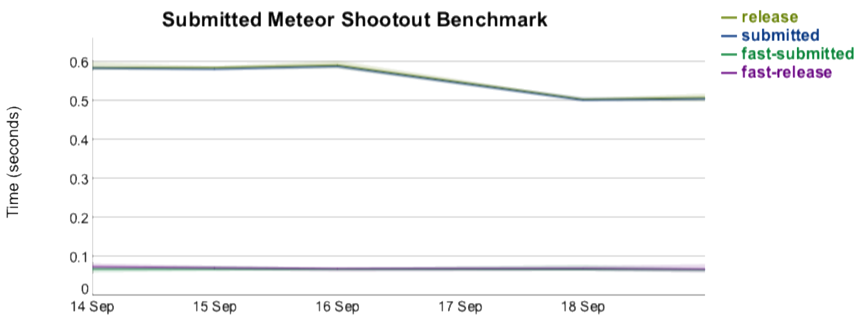
Array Indexing Opt: Impact

- **Saw significant performance improvements**
  - several shootout benchmarks also benefited (lower is better)









Array Indexing Opt: Status and Next Steps

Status:

- added an array indexing optimization
  - indexing into 1-D arrays is as efficient as C/C++ arrays
  - optimization is thwarted if any arrays require this multiplication

Next Steps:

- finish ”array-views” work
  - retire current compiler optimization

Promoted Fast Followers Improvements

Fast Promotion: Background

- **Chapel supports promoted expressions**

```
var A, B, C: [1..m] real;
A = B + alpha * C;
```

- **Promotion is implemented using zippered iteration**

  The promoted expression:

```
A = B + alpha * C;
```

  Is semantically equivalent to:

```
forall (a, b, c) in zip(A, B, C) do
  a = b + alpha * c;
```

- **Historically, promotion could hurt performance**
  - compiler did not build support for promoted fast-followers
    - fast followers: optimize zippered iteration for aligned distributed arrays
    - hurt performance for aligned promotion relative to explicit zippering

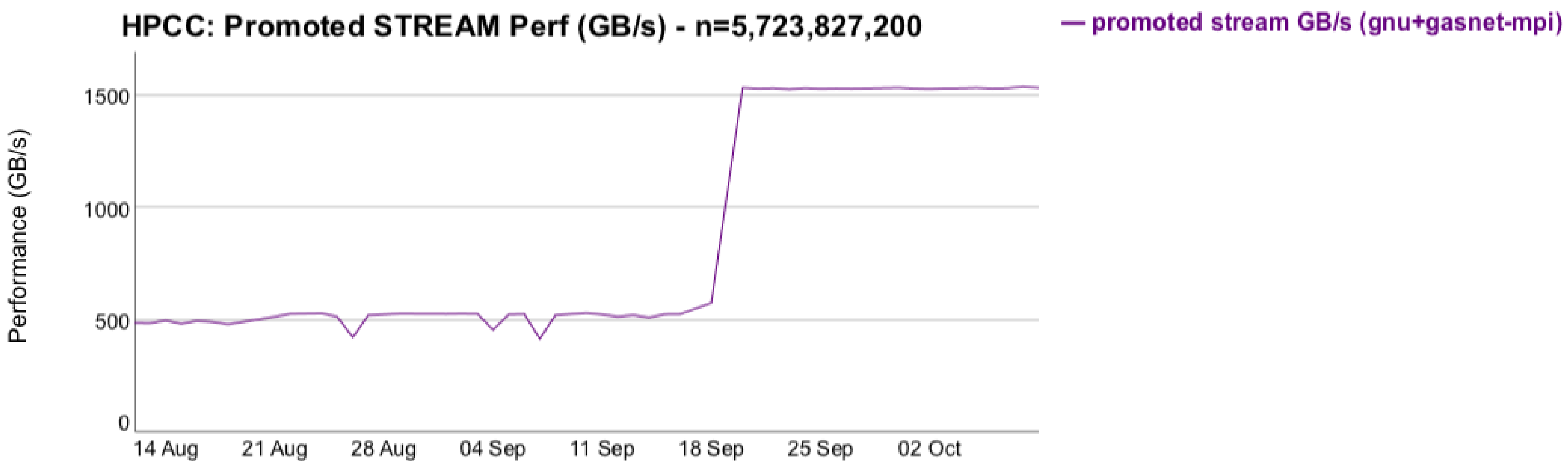
Fast Promotion: This Effort and Impact

This Effort: add support for promoted fast followers

- compiler builds checks required for fast-followers to trigger
  - at compile time: check that the promoted types support fast-followers
  - at runtime: check that promoted arrays are aligned (distributed identically)

Impact: improved performance of promoted expressions

- no longer any penalty for using promotion



Fast Promotion: Next Steps

Next Steps: eliminate runtime checks when possible

- arrays declared over the same distribution must be aligned

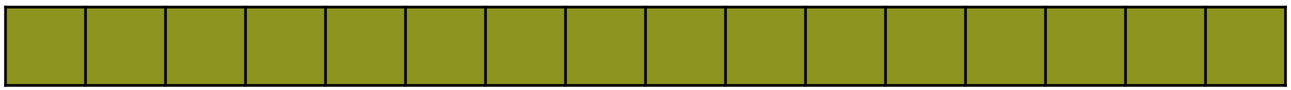
```
var A, B: [distDom] real; // alignment known at compile time

var A: [distDom1] real;
var B: [distDom2] real;     // alignment must be checked at runtime
```

Strided Bulk Transfer

Strided Bulk Transfer: Background

- **Whole-array assignment can use a single GET or PUT**

```
var A, B : [1..4, 1..4] int;
A[1..4, 1..4] = B[1..4, 1..4];
```



- **Slicing may select non-contiguous memory**

```
A[1..4, 1..2] = B[1..4, 3..4];
```

- **Can still bulk-transfer elements contiguous in memory**

Strided Bulk Transfer: Background

- **Initial implementation based on GASNet support**
  - Based on approach described by Dan Bonachea
    - http://upc.lbl.gov/publications/upc_memcpy.pdf
  - Contributed by Rafael Asenjo and Alberto Sanz (U. Malaga) for v1.6

- **Calls out to runtime functions to perform transfers**
  - Uses GASNet's interface when possible
  - Otherwise uses our own implementation for each comm layer
  - Module code computes necessary metadata about arrays

- **Enabled through 'useBulkTransferStride' config param**
  - Disabled by default due to lack of confidence in testing

Strided Bulk Transfer : This Effort

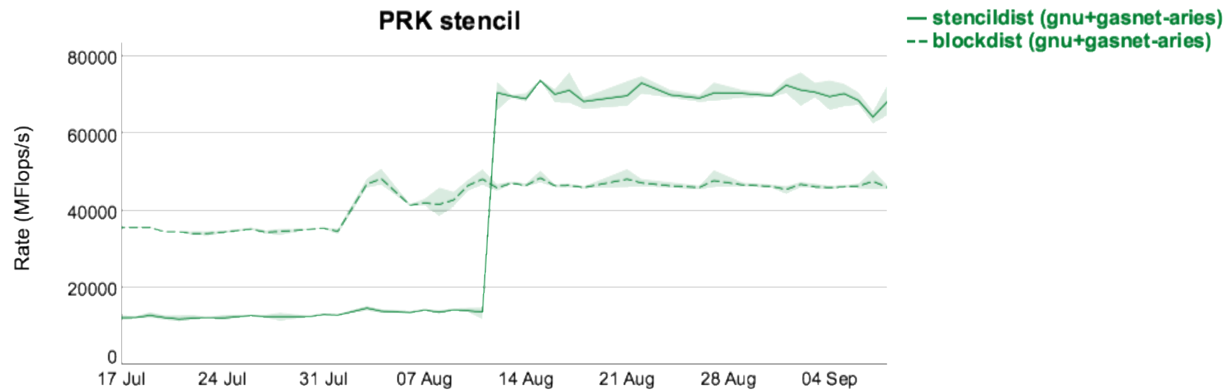
- **Significantly improved the implementation**
  - Fixed several bugs
  - Simplified code implementation
  - Revamped documentation

- **Improved testing for DefaultRectangular cases**
  - Rank changes
  - Strided domains
  - Many combinations of domains up to four dimensions

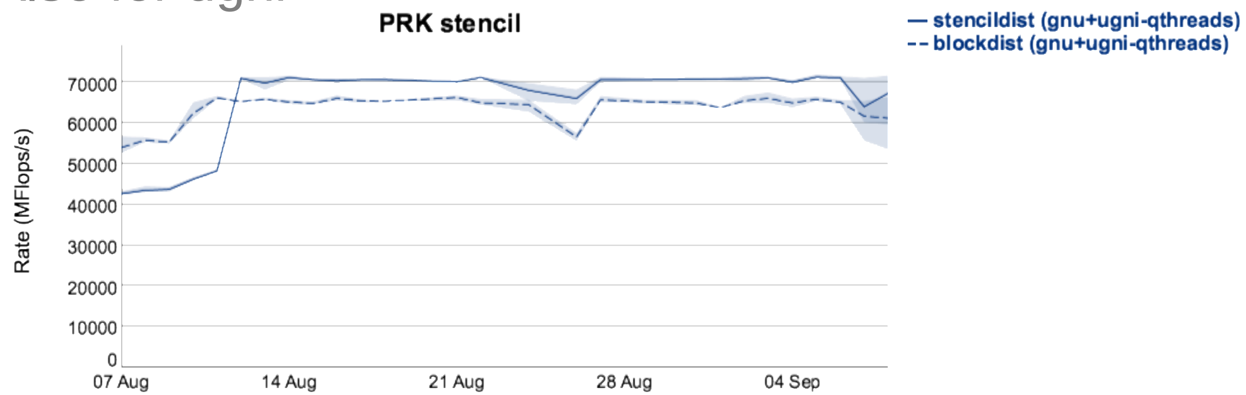
- **Enabled this optimization by default**
  - Good performance observed for Intel PRK Stencil app

Strided Bulk Transfer : Impact

- **Good improvements for PRK stencil**
  - Especially for GASNet



  - Also for ugni



Strided Bulk Transfer : Status and Next Steps

Status:

- Enabled by default for the 1.14 release

Next Steps:

- Investigate distributed array strided bulk transfer
- Module-level implementation for runtimes without custom support?

Array-as-vec Shrinking Improvement

Array-as-vec Shrinking Improvement

Background: Shrinking an array-as-vec left no room for growth

- After a shrink, the allocated size was set to the current array size
- Then push/popping a few elements could cause repeated reallocation

This Effort: Leave room for growth after shrinking the array

- Leave the allocation `growthFactor` times bigger than the number of array elements

Impact: Push/popping a few elements won't cause repeated resizing

Locality Optimizations

Wide Pointer Analysis Improvements

Wide Pointer Analysis: Background

- **Wide pointers represent remote data**

```
typedef struct {
  locale_id_t node;
  myClass*    addr;
} chpl__wide_myClass;
```

- **They introduce overhead when data is actually local**
  - Especially for array accesses
  - Runtime check required to see if data is local
  - Wide pointers may thwart back-end C compiler optimizations

Wide Pointer Analysis: Background

- Passing a wide pointer to a function has consequences

```
proc increment(this: myClass) {
  this._internalAdd(1);
  return this;
}
var foo = new myClass();
foo.increment(); // internally becomes increment(foo)

on Locales[numLocales-1] {
  // 'foo' is remote in this scope, so 'this' formal must be wide
  foo.increment();
}
```

- 'increment' will always return a wide pointer, even for local data

```
// types for 'increment' must change during compilation
proc increment(this: chpl__wide_myClass) {
  this._internalAdd(1);
  return this; // now a wide pointer!
}
```

Wide Pointer Analysis: Background

- **'increment' example is artificial, but this occurs in practice**
  - Array, domain, distribution constructors
  - Array slicing

- **For non-trivial programs, we eventually use a wide array**
  - Especially when domain maps are used

- **At callsite, the returned pointer refers to local data**

```
var foo = new MyClass();
foo.increment(); // 'foo' is local, but increment returns wide
```

  - Problem: the compiler could not detect this in 1.13

Wide Pointer Analysis: This Effort

- **Develop analysis to detect that the returned data is local**
  - If we pass in a local class, get a local class back
  - Passing in a wide class, gets a wide class back

- **Find functions that 'reflect' the wide-ness of arguments**
  - Reflects if returned symbol would be local if arguments are local

- **At a callsite, localize the returned wide pointer**
  - When the arguments are also local

Wide Pointer Analysis: This Effort

- **Consider the 'increment' function**
  - Where 'foo' is a **local** variable
    - Before this effort:

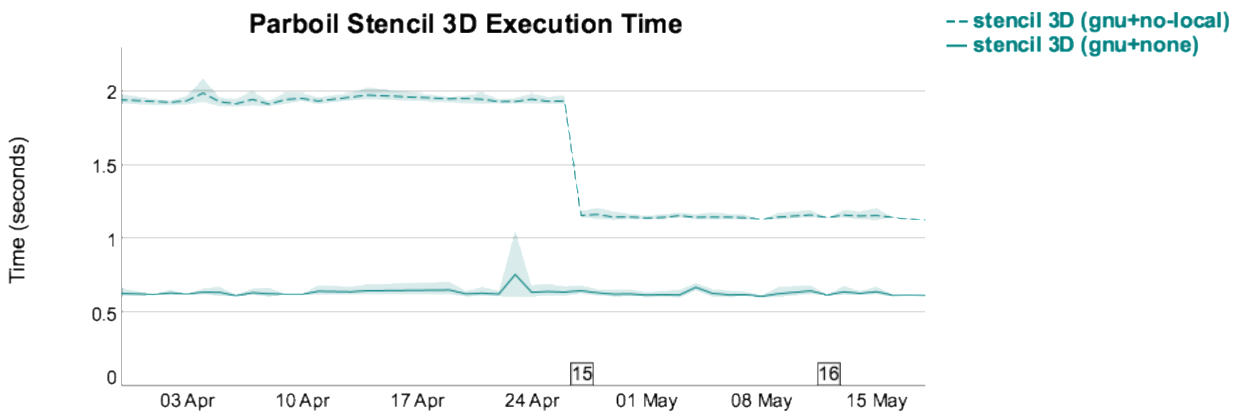
```
var temp : wide__myClass = increment(foo);
```

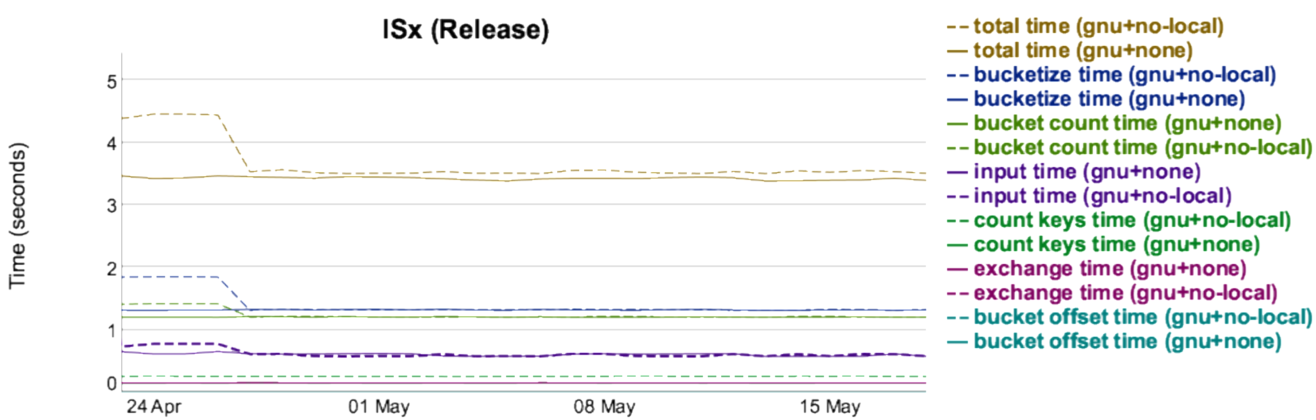
    - After analysis:

```
var wideTemp : wide__myClass = increment(foo);
var temp     : myClass       = wideTemp.addr; // The local pointer

// 'temp' is now local and avoids wide-pointer overhead for subsequent operations
```

Wide Pointer Analysis: Impact

- **Improvements for single-node –no-local**
  - Minimal impact, if any, on true multi-locale





Wide Pointer Analysis: Status and Next Steps

Status:

- New analysis enabled for 1.14 release
- Improves generated C code
- Performance gains less than hoped for

Next Steps:

- Improve analysis for return-by-reference formals
- Look for other patterns where this analysis is useful

Reducing Task Counting Overhead

Task Counting: Background

- **coforall statements wait for their tasks to complete**
  - implemented with atomic variables
  - when coforall spawns each task, the atomic variable is incremented
  - when a task completes, it decrements the atomic variable

- **But, decrementing created a new task!**
  - on the locale that owns the atomic variable
  - this is unnecessary overhead

Task Counting: Background

```
coforall loc in Locales {
  on loc {
    foo();
  }
}
```

// is converted by the compiler into something like this:

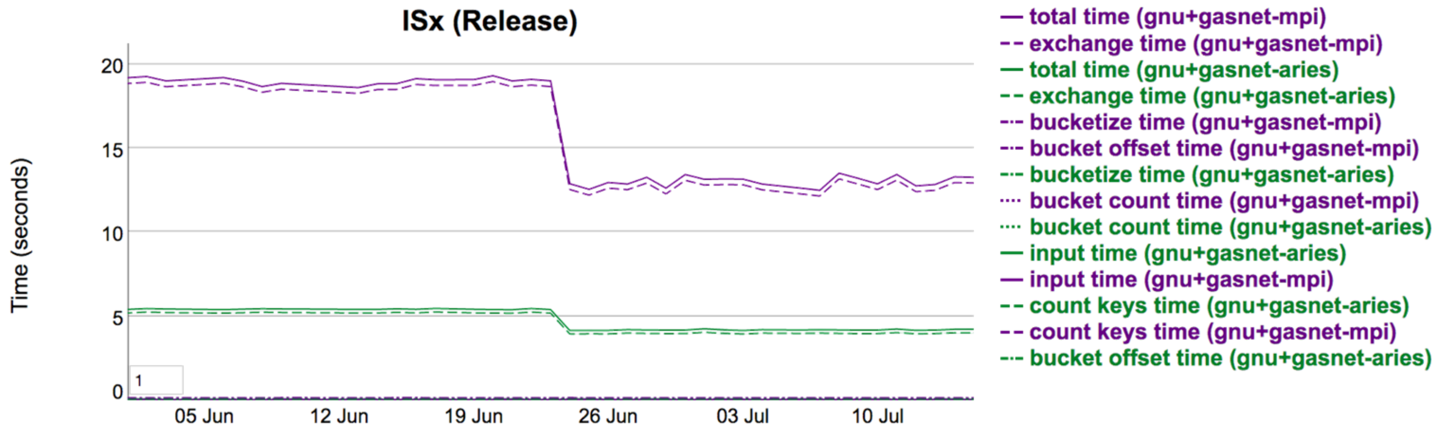
```
var tasksRunning: atomicInt; // processor atomic
for loc in Locales {
  tasksRunning.add(1);
  spawn_task_to_loc(loc, foo_wrapper());
}
tasksRunning.waitFor(0);

foo_wrapper() {
  foo();
  on Locales[0] do tasksRunning.sub(1);
}
```

Overhead: creates a task on Locale 0

Task Counting: This Effort

This Effort: Make compiler smarter about these decrements
- perform them in active message handler
- no need to start a task

Status:
- Implemented and in the release
- Improved performance of some tests, e.g. for this 16-node XC run:



Next Steps:
- Make additional short operations run in active message handlers

Reducing Overhead for Local On Statements

Local On: Background

- **Programs often have on-statements that run locally**
  - these are commonly there for generality
- **Some common examples:**
  - I/O from Locale 0
  - updating atomic values
- **These on-statements still add overhead because:**
  - an argument bundle is allocated
  - arguments are stored into the argument bundle
  - the runtime is invoked to possibly communicate

Local On: This Effort

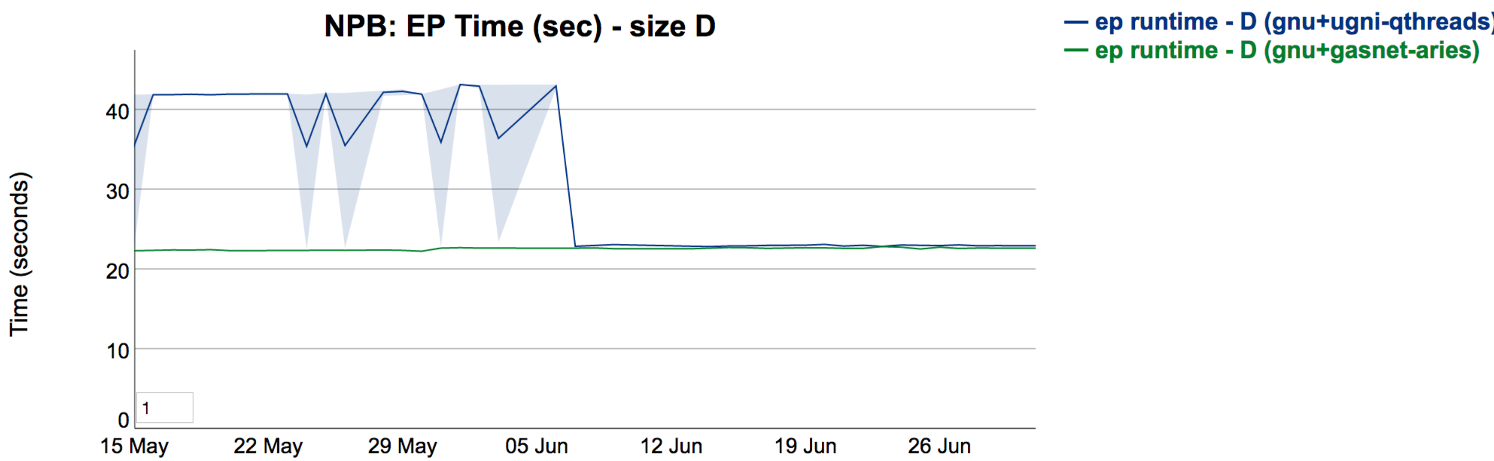
- **Compiler now generates a fast-path for on-statements**

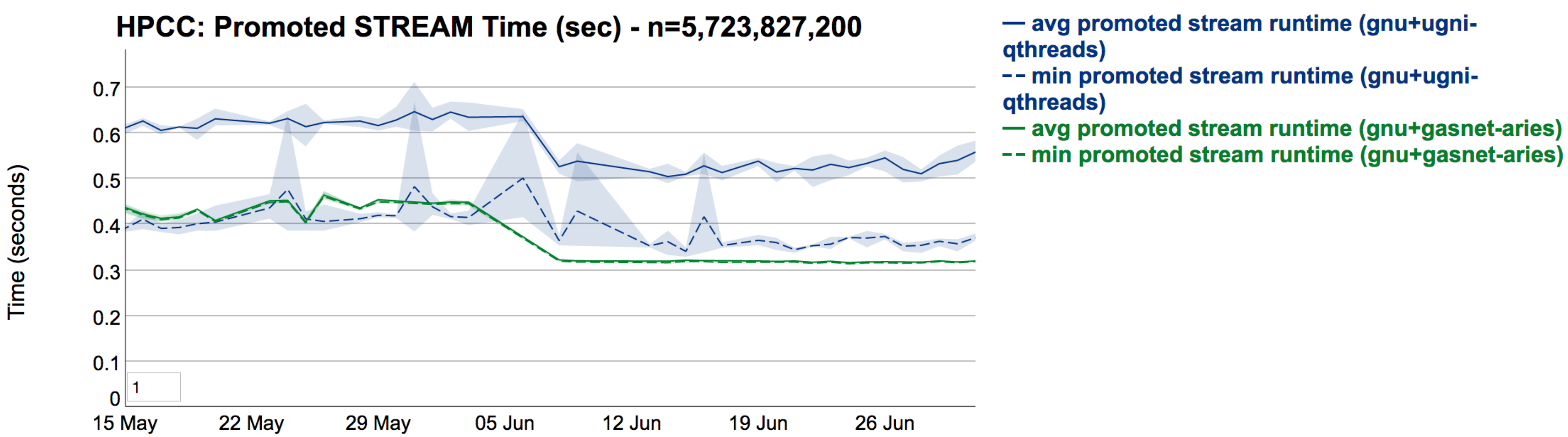
```
on targetLocale do f(a, b, c);
```

now translates into

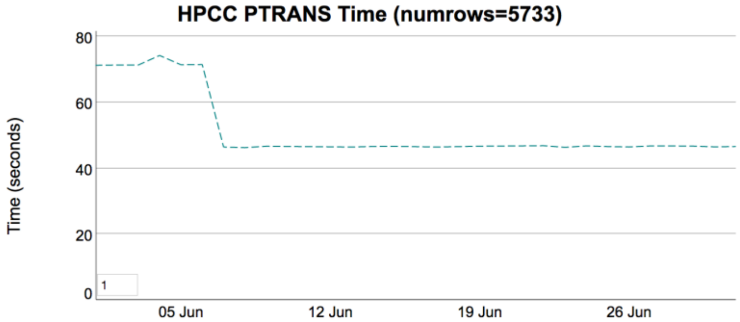
```
if (targetLocale == thisLocale) {   // local case
  f(a, b, c);
} else {                            // remote case
  arguments = malloc(...);
  arguments->a = a;
  arguments->b = b;
  arguments->c = c;
  chpl_executeOn( targetLocale, &f_wrapper );
  free(arguments);
}
```

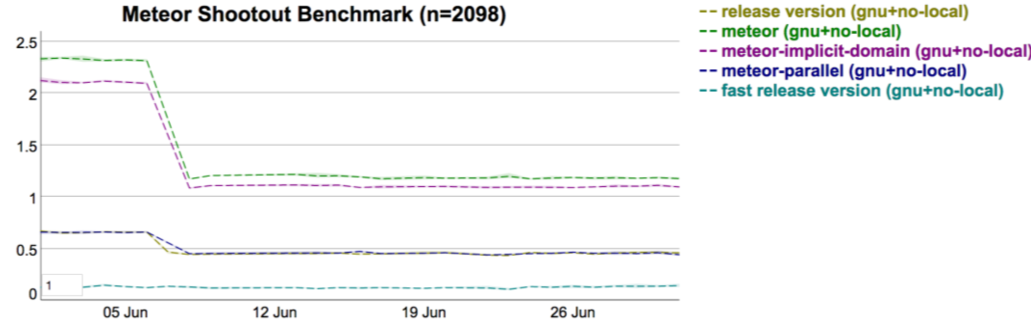
Local On: Impact on 16-node XC

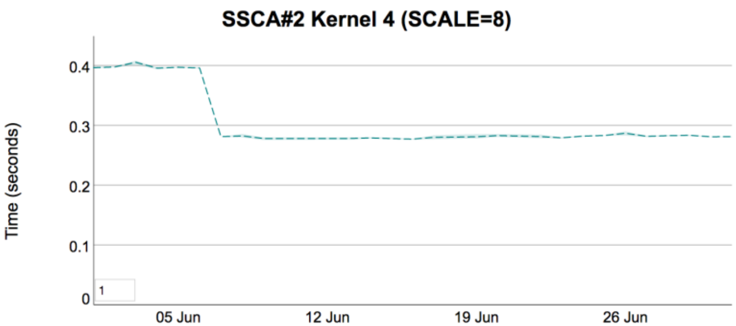


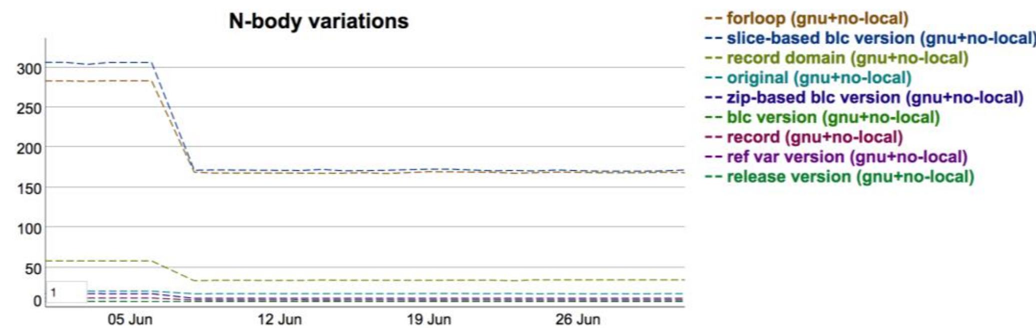


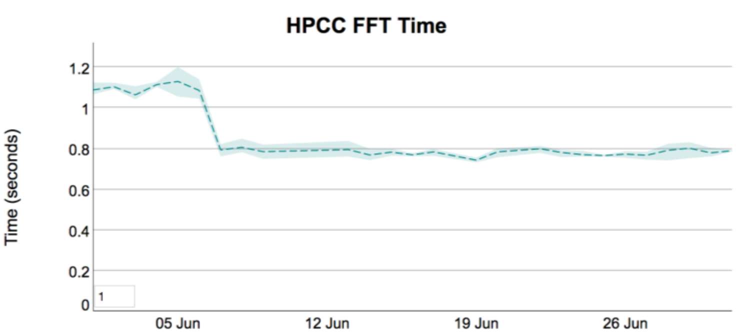
Local On: Impact on --no-local tests

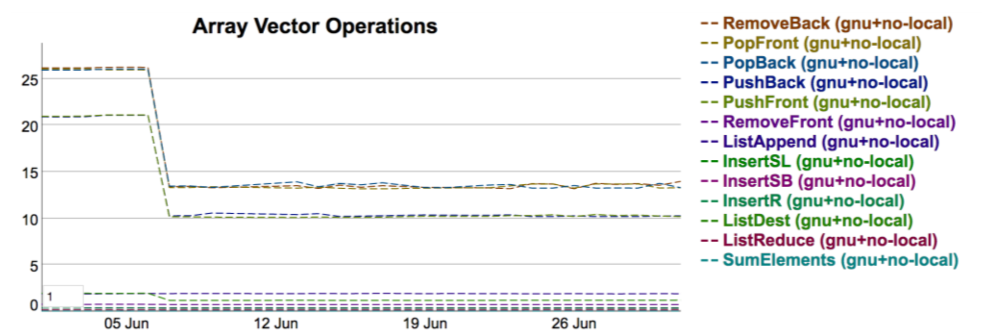












Local On: Status and Next Steps

Status:

- Optimization implemented
- Good improvement to --no-local compilation
- Some improvement in 16-node XC performance testing
- Reduces the number of cache flush events with --cache-remote

Next Steps:

- Apply the optimization to non-blocking on statements
- Fold away the remote case within local blocks

Qthreads Improvements

Native Qthread Sync Vars

Qthread Sync Vars: Background

Chapel Sync Var History:

- historically, Chapel permitted any type to be declared 'sync'/'single'
  - this was thought to be attractively general and orthogonal — for example:

```
var A$: [1..n] sync int;      // an array of synchronized integers
var B$: sync [1..n] int;      // a synchronized array of integers
```

  - synchronized arrays could be interpreted sensibly in some cases:

```
B$ = 0;                       // block until B$ is empty; zero; leave full
```

  - but others were less clear:

```
B$[3] = 1;                    // how should full/empty state be involved?
```

  - records, complexes had similar issues
- some time ago, decided sync/single should support simple types only
  - effectively, ones with a single logical value (int, bool, uint, real, imag, etc.)
  - compiler started enforcing that decision as of 1.13

Qthread Sync Vars: Background

Chapel Background:

- runtime support for sync/single has traditionally been heavyweight
  - because of historical support for sync/single on arbitrary data types
- a faster/simpler implementation is possible for simple data types

Qthreads Background:

- Qthreads was designed to emulate the Cray XMT architecture
  - has native sync var support because XMT had native sync vars
  - left out operations not typically needed in apps (readXX, writeFF, reset)

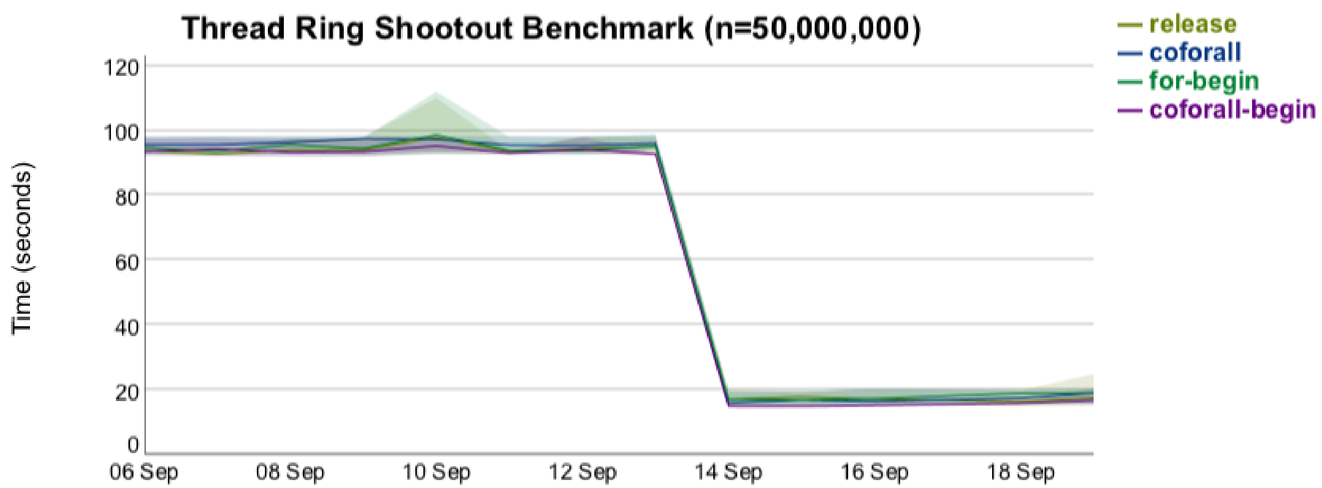
Qthread Sync Vars: This Effort

- **Implemented missing Qthreads sync var operations**
  - with lots of help from one of the original Qthreads developers
  - contributed upstream, included in Qthreads 1.11 release

- **Map Chapel sync vars down to native Qthreads versions**
  - currently implemented for int/uint/bool types
  - other data types don't trivially cast to qthreads sync var type
    - they fall back to the heavy-weight implementation

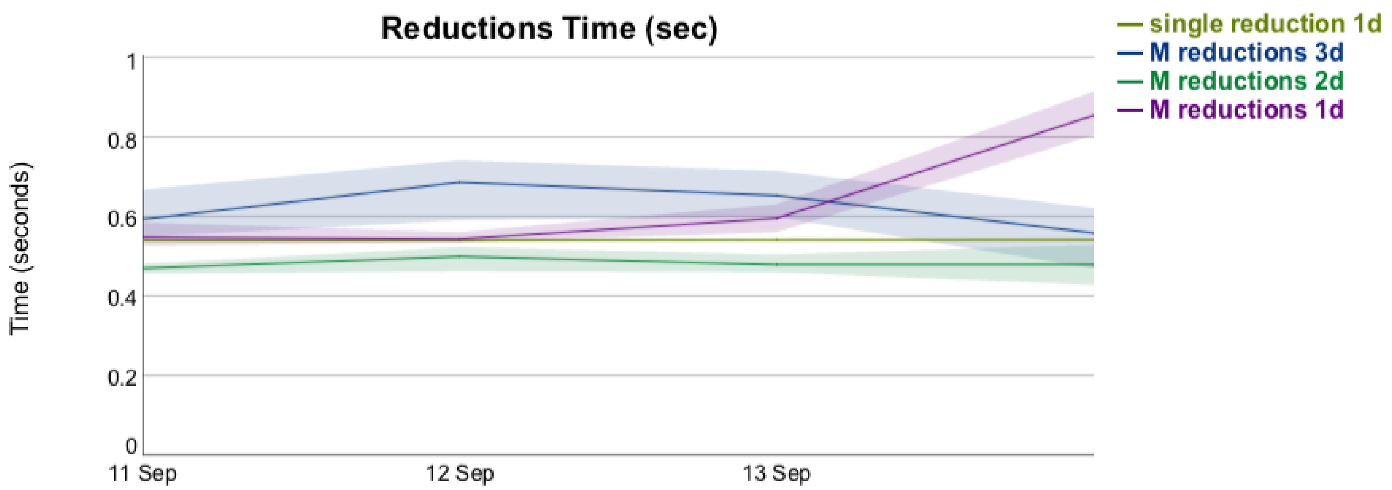
Qthread Sync Vars: Impact

- Dramatically improved perf of highly-contended syncs



Qthread Sync Vars: Impact

- **Hurt reduction performance**
  - regressions were then improved by using an atomic lock (next section)



Qthread Sync Vars: Impact

- **Hurt performance of reductions (cont.)**
  - reductions use a minimally-contended, short-lived lock to accumulate
  - perf loss indicates that qthreads sync var creation time is expensive
  - partially caused by unnecessary hash table manipulation
    - Qthreads uses a hash-table to correlate sync vars to F/E queues/state
    - full vars that have no pending ops are removed from the hash-table
    - this results in unnecessary hash table insertions/removals

```
// reduction accumulation code for each task
lock.writeEF();          // lock – fills (no pending ops): hash entry removed
accumReduction();
lock.readFE();           // unlock – empties: hash entry inserted
```

    - Chapel sync vars are only deleted when they go out of scope
    - want to keep qthreads syncs in hash-table until Chapel destroys them

Qthread Sync Vars: Status and Next Steps

Status:

- added missing sync var operations to qthreads
- mapped Chapel sync vars down to native qthreads sync vars
  - resulted in substantial performance boost for highly-contended sync vars
  - hurt performance for minimally-contended, short-lived sync vars

Next Steps:

- improve performance for short-lived sync vars
  - start by eliminating extra hash table manipulations
- use native qthread sync vars for more Chapel types
  - will require using memcpy in order to "cast" to qthreads sync var type

Reduction Lock Improvements

Reduction Lock: Background and This Effort

Background: reductions have used a sync var as a lock

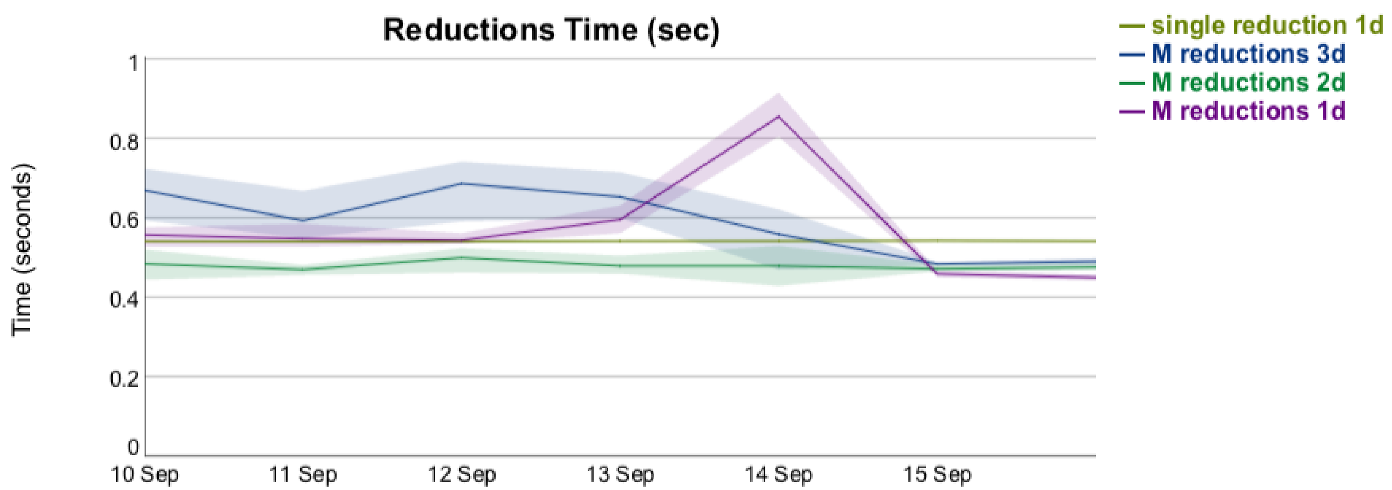
- lock is needed to accumulate parallel reductions
- Implemented as a sync var before atomics were introduced to Chapel
- switching to native qthread sync vars hurt reduction performance
  - qthread sync vars are relatively expensive to create
- accumulation is a short-lived, minimally-contended operation
  - spin-locks are better for this situation

This Effort: use an atomic spin-lock instead of a sync var

- implemented as an exponential backoff testAndSet loop

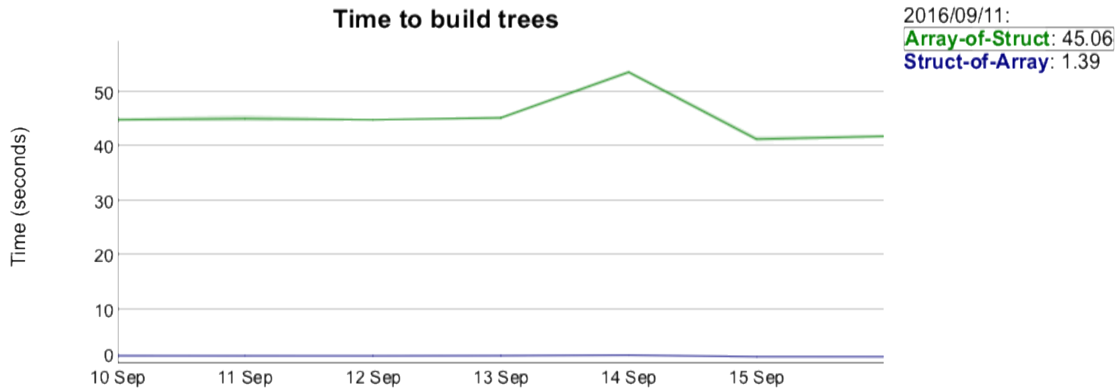
Reduction Lock: Impact and Status

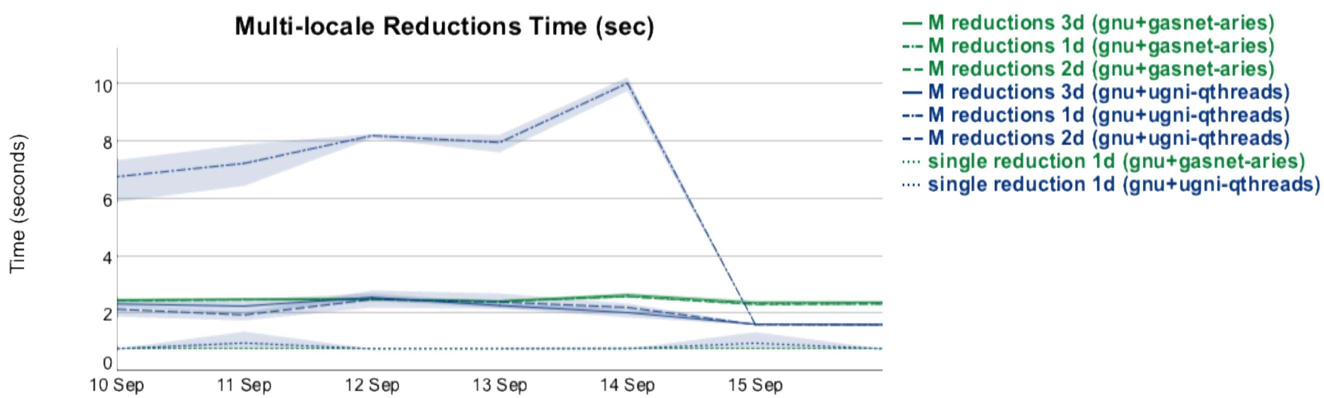
- Improved reduction performance
  - resolved regressions caused by qthread sync vars



Reduction Lock: Impact and Status (cont.)

- Improved reduction performance
  - in many cases, performance is even better than it had been before





New Qthreads “Distrib” Scheduler

Distrib Scheduler: Scheduler Background

- **Qthreads has several scheduler options**
- **“nemesis” is our default**
  - simple, but fast
  - no work-stealing
    - new tasks distributed to queues round-robin, never re-balanced
  - no numa-awareness
- **“sherwood” was our default for the NUMA locale model**
  - numa-aware (required by NUMA locale model)
  - support for work-stealing
    - new tasks placed in a single queue, work-stealing required to balance
  - too slow to be our default everywhere

Distrib Scheduler: Sherwood Background

- **Sherwood was tuned for Unbalanced Tree Search (UTS)**
  - UTS presents significant load imbalance
    - fast solutions require dynamic load balancing using many tasks

- **Sherwood has very aggressive work-stealing**
  - ideal for UTS, horrible for balanced workloads
    - idle threads continuously try to steal, even when no work is available
  - disabling work-stealing cripples the scheduler
    - work distribution requires stealing, new tasks are added to a single queue

- **Overall, sherwood had poor performance**
  - especially for applications with balanced workloads

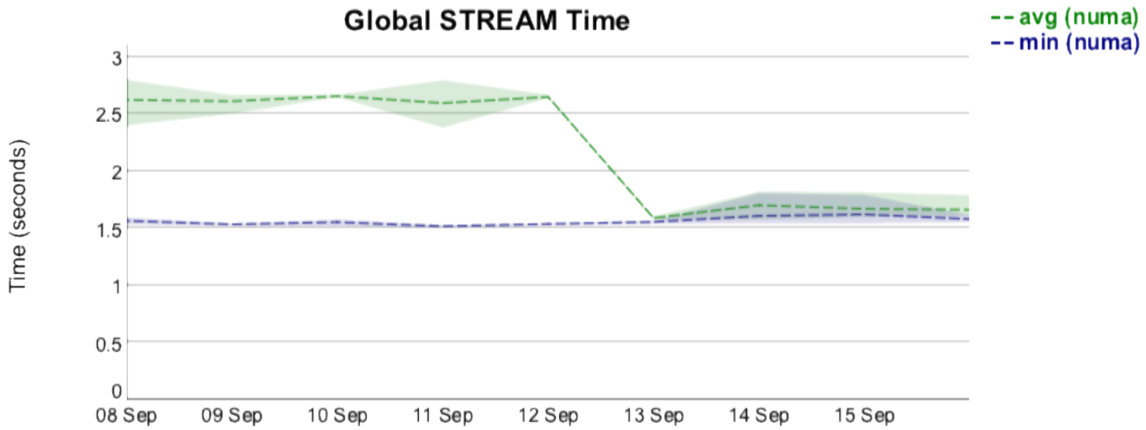
Distrib Scheduler: This Effort

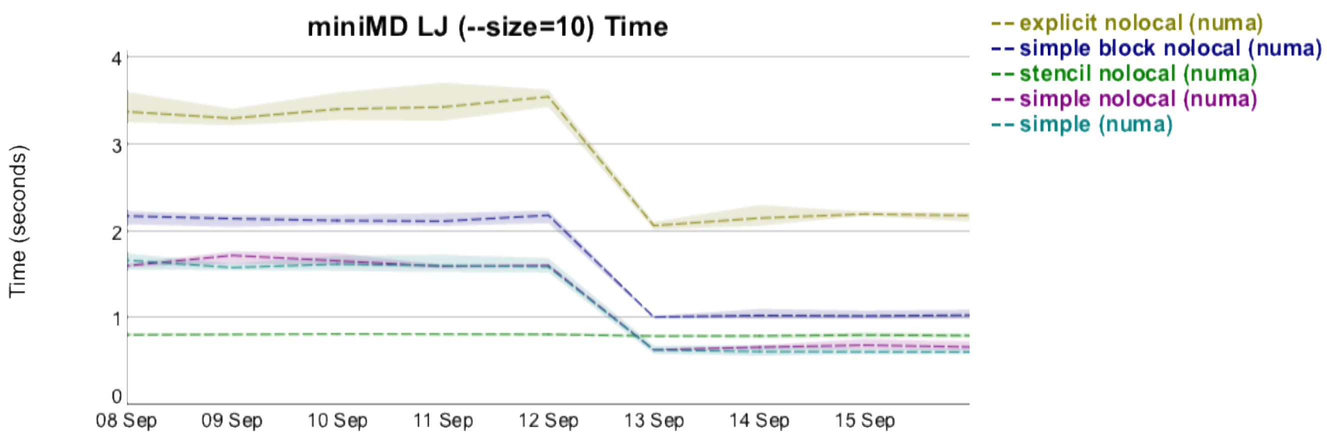
- **Qthreads team developed a new scheduler**
  - Qthreads team initially tried to improve sherwood scheduler
    - proved too difficult, so a new distrib scheduler was created
  - we worked closely with the Qthreads team to tune performance
    - iterated through many contention management and work-stealing strategies
  - as a result, distrib is a huge improvement over sherwood
    - significantly faster than sherwood, competitive with nemesis
    - still has support for work-stealing
    - still numa-aware

- **Made distrib our default scheduler for numa**
  - currently disable work-stealing by default
    - needed more time to tune performance

Distrib Scheduler: Impact

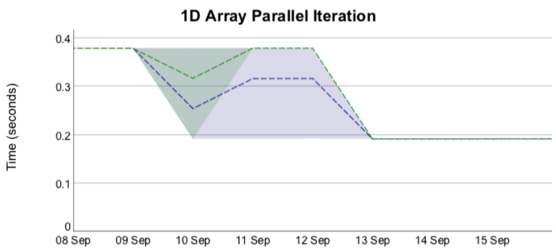
- Significant performance improvements for numa

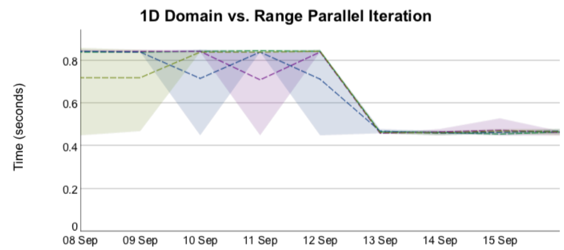


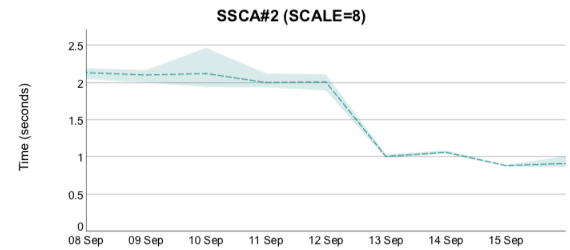


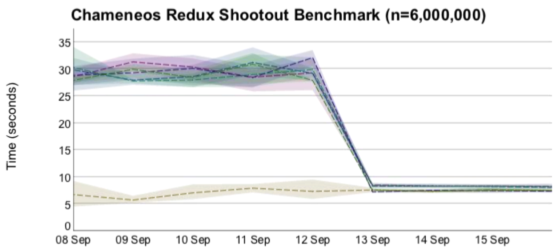
Distrib Scheduler: Impact

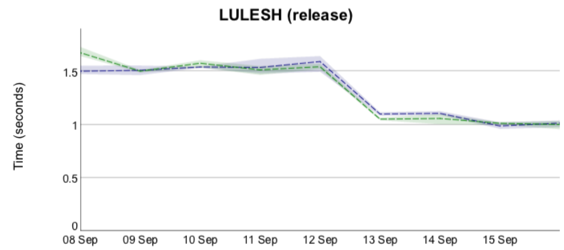
- **Significant performance improvements for numa**
  - … lots of them

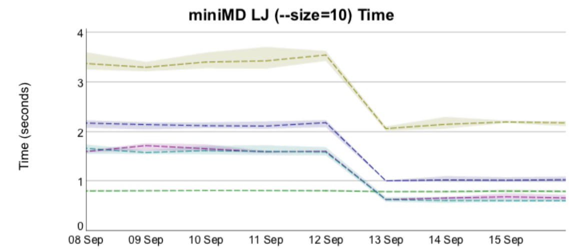


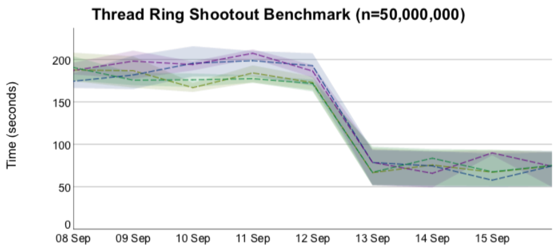


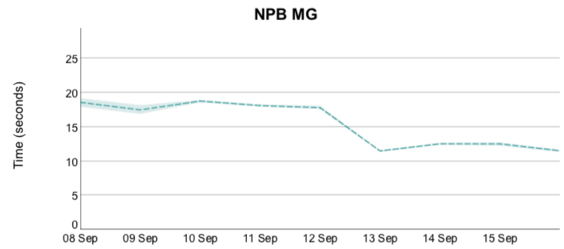


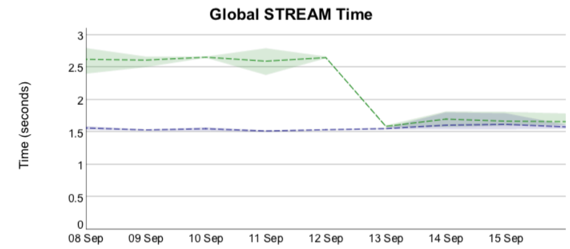












Distrib Scheduler: Status and Next Steps

Status:

- new distrib scheduler is being used for numa
  - results in significant performance improvements

Next Steps:

- continue to tune distrib scheduler
  - close remaining gap with nemesis, and default to distrib everywhere
- tune work-stealing algorithm
  - make the overhead small enough that we can enable it by default

Runtime Improvements

Jemalloc Changes

Jemalloc: Overview

- **Jemalloc is a general-purpose malloc implementation**
  - "scalable concurrency support"
  - "emphasizes fragmentation avoidance"
  - also supports an extended API
    - good alloc size, sized deallocation, etc.

- **Actively maintained on GitHub**
  - https://github.com/jemalloc/jemalloc

- **Large number of notable users**
  - FreeBSD and NetBSD
  - Mozilla Firefox
  - Facebook
  - Rust
  - Chapel!

Jemalloc: Portability Improvements

Background: made jemalloc our default memory layer in 1.13

- resulted in significant performance improvements
- however, we couldn't use jemalloc in a few configurations:
  - cce (build issues, but we worked around them in our makefiles)
  - osx+gnu (build issues)
  - pgi (segfaults at execution time)

This Effort: Improved portability for cce, osx+gnu, and pgi

- patches accepted upstream, will be in the next jemalloc release
  - manually applied to our copy of jemalloc in the meantime

Impact: jemalloc is now our default everywhere

- (except under cygwin, but cygwin performance is not a priority)

Jemalloc: Performance Improvements

Background: saw significant performance benefits with jemalloc

- jemalloc is frequently released, often with performance improvements
- we initially used the default configuration options

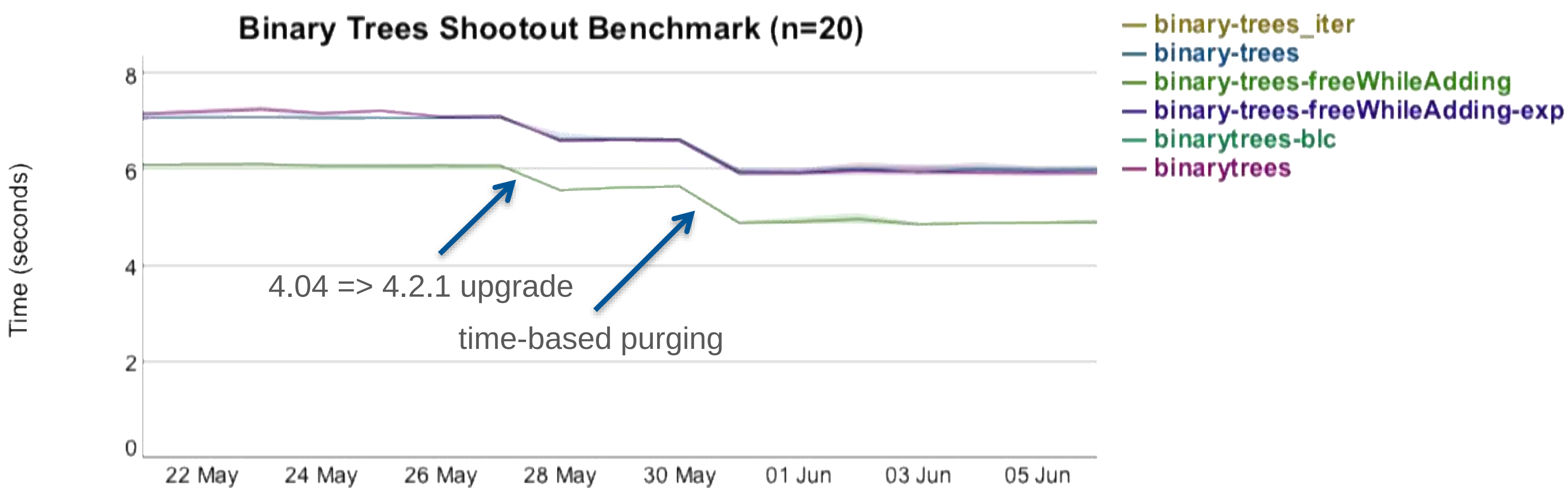
This Effort: upgraded jemalloc and streamlined configuration

- upgraded from jemalloc 4.0.4 to 4.2.1
- enabled a new time-based purging optimization
  - improves mechanism for returning memory to the OS
  - opt-in for 4.X, will likely be the default for 5.X
- disabled stats gathering by default
  - stats gathering is highly optimized, but still has a non-zero cost
  - to enable, set CHPL_JEMALLOC_ENABLE_STATS at build-time

Jemalloc: Performance Improvements

Impact: additional performance improvements

- saw performance improvements for several benchmarks
  - most notably for binary trees, which had > 20% speedup



Jemalloc: Summary and Next Steps

Summary:

- improved jemalloc's portability
  - for cce, pgi, and osx+gnu
- improved jemalloc's performance
  - through version upgrade and configuration optimization

Next Steps:

- use more of the extended API
  - add support for sized deallocation
  - use good_alloc_size() in more places (e.g., array-as-vector)
- use jemalloc for third-party libraries
  - this is already being done for GMP
  - would have the most impact for qthreads, and possibly re2

Faster complex.re and complex.im

Faster complex.re and complex.im

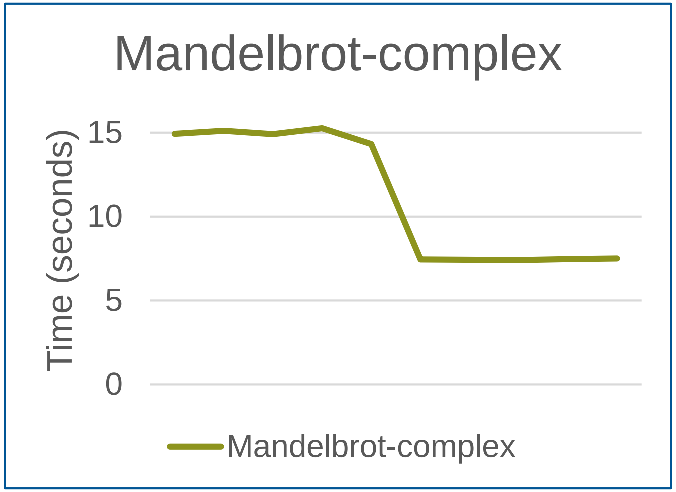
Background: `.re` and `.im` were slower than record field accesses

This Effort: Optimize them to match record access speed

Impact: Codes that use `.re` and `.im` got a performance boost

Mandelbrot-complex inner loop

```
for 1..maxIter {
  if (T.re + T.im > limit) then
    break;
  // Z = Z*Z + C
  Z.im = 2.0*Z.re*Z.im + C.im;
  Z.re = T.re - T.im + C.re;
  T.re = Z.re**2;
  T.im = Z.im**2;
}
```



Other Performance Optimizations

Other Performance Optimizations

- Optimized base**exp when 'base' is a param power of two

```
2**k => 2<<(k-1)
8**k => 8<<(3*(k-1))
```

- Eliminated compiler-created tuple for zippered serial loops

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