Performance Optimizations
Generated Code Improvements

Chapel Team, Cray Inc.

Chapel version 1.11

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Outline

- Anonymous Range Iteration Optimization
- Vectorization
- Parallel Range Iteration Optimization
- Loop-Invariant Code Motion (LICM) Update
- The "local field" pragma
- The "assertNoSlicing" config param
- External Procedures with 'string' Arguments
- Other Performance Improvements
- Optimization/Codegen Priorities and Next Steps

Anonymous Range Iteration Optimization

Anonymous Range Opt: Background

- **Anonymous ranges: those not stored in a named variable**
  - cannot be referenced elsewhere
  - commonly used directly in a loop

```
for i in 1..10 do
for i in lo..hi do
```

- **Ranges are implemented as records**
  - as a result, each range literal constructs a record object
  - anonymous ranges are not captured and cannot be used again
    - so why waste time constructing them?

Anonymous Range Opt: This Effort

- **Eliminate construction for common anonymous ranges**
  - provide an optimized iterator when stride is known at compile time
  - eliminate cost of construction
  - permits generating loop termination with <= or >= rather than !=
    - (OpenMP/OpenACC pragmas can't be attached to loops terminated by !=)
  - allow back-end compiler to better optimize and auto-vectorize

- **Optimization occurs at parse time**
  - for-loop builder recognizes certain range patterns
  - replaces those with a direct range iterator
    - iterator takes low, high, stride as arguments
    - e.g., compiler replaces:

```
for i in 1..10 do
```

with:

```
for i in chpl_direct_range_iter(1, 10, 1) do
```

Anonymous Range Opt: Impact

- **Eliminates range construction for many common cases**

```
for i in 1..10 do writeln(i);
```

previously:

```
_build_range(INT64(1), INT64(10), &call_tmp);
low = (&call_tmp)->_low;
high = (&call_tmp)->_high;
for (i = low; i <= high; i += INT64(1))
  writeln(i);
```

now:

```
for (i = INT64(1); i <= INT64(10); i += INT64(1))
  writeln(i);
```

Anonymous Range Opt: Impact (continued)

- **Optimized iteration for strides known at compile time**

```
for i in 1..10 by 2 do writeln(i);
```

previously:

// function call to build range
// function call to apply 'by' operator to range
// function call and conditional check to see if range is ambiguous
// function call to compute the starting value
// conditional check to see if range is empty (e.g. 2..1)
// function call to compute the ending value

71 SLOC

```
for (i = start; i != end; i += str)  // finally iterate, but using !=
  writeln(i);
```

now:

```
for (i = INT64(1); i <= INT64(10); i += INT64(2))
  writeln(i);
```

Anonymous Range Opt: Impact (continued)

- **Stridable anonymous ranges amenable to offload pragmas**
  - when stride is known at compile time

- **Better back-end optimization and auto-vectorization**
  - range construction and other checks obfuscate iteration pattern
  - we now propagate range literals directly to the C for loop
    - helps create cleaner vectorized code (eliminates some loop peeling)
    - allows compiler to better select unrolling factor and trip count

- **No major changes seen in nightly performance graphs**
  - not terribly surprising
    - most time spent in loop body, not prelude
    - not many benchmarks iterate over nested anonymous ranges
    - lacked performance testing with modern vectorizing back-end compilers
      - have since started testing with the newest versions of Cray, GNU, Intel, and PGI

Anonymous Range Opt: Status

- Cases that are currently handled

```
for i in 1..10 do                               // works for simple ranges
for i in 1..10+1 do                             // works with expressions in ranges
var lo=1, hi=10; for i in lo..hi do             // works for variables
for i in 1..10 by 2 do                          // works for strided ranges
for (i, j) in zip(1..10, 1..10) do              // works for zippered iters
for (i, j) in zip(A, 1..10) do                  // following non-ranges also works
coforall i in 1..10 by 2 do                     // works for coforalls as well
```

- Cases that are not handled

```
for i in (1..) do                   // doesn't handle unbounded ranges
for i in 1..10 by 2 by 2 do         // doesn't handle more than 1 'by' operator
for i in 1..10 align 2 do           // doesn't handle 'align' operator
for i in 1..#10 do                  // doesn't handle 'count' operator
var r = 1..10; for i in r do        // not an anonymous range
forall i in 1..10 do                // does not get applied to foralls
```

Anonymous Range Opt: Next Steps

- **Handle additional cases**

```
for i in 1..#10 // used frequently in leader and standalone iterators
```

- **Move optimization from parse-time to after resolution**
  - requires that resolution is moved before normalization
  - would allow us to handle more cases
    - …and not be so careful about preserving user errors
  - would allow us to anonymize named ranges used only for iteration

```
var r = 1..10;
if debugParam then writeln(r);      // common in our iterators
for i in r do yield i;

var r = 1..10;
for i in r do A[i] = i;
for i in r do A[i] = A[i%10+1]; // common in benchmarks & user code
```

Vectorization

Vectorization: Background

- **Vectorization is crucial for achieving peak performance**
  - true for commodity and HPC systems
  - becoming increasingly important, particularly in HPC
    - AVX-512 (Xeon and Xeon Phi)
    - NEON (ARM)

- **Chapel relies on back-end compiler to auto-vectorize**
  - Chapel's primary back-end generates C code
  - C compilers are frequently thwarted by memory aliasing
    - must make conservative assumptions that inhibit auto-vectorization

Vectorization: Background (continued)

- **Chapel is well-suited for vectorization**
  - limited aliasing
  - support for array programing

    ```
    A = B + C;
    ```
  - parallelism is a first class citizen

    ```
    forall i in 1..10 do …
    ```

- **Need to convey Chapel semantics to back-end**
  - do not want to generate explicit vectorization
    - rather, convey when vectorization is legal
    - leverage back-end compilers' sophisticated and refined cost models

Vectorization: Background (continued)

- **Data-parallel operations are vectorizable**
  - user asserts there are no data dependencies or ordering constraints

```
A = B + C;
forall i in 1..n do A[i] = B[i] + C[i];
forall (a, b, c) in zip(A, B, C) do a = b + c;
```

- **Data-parallelism implemented in terms of task-parallelism**
  - for zippered case…
    - leader iterators create parallelism and assign work to followers
    - follower iterators serially do the chunk of work assigned by the leader
      - work assigned to followers should have no vector dependencies
  - in standalone case, iterator creates parallelism *and* does serial work
    - again, serial work should have no vector dependencies
    - here, we'll call this serial work "follower loops" for simplicity

Vectorization: This Effort

- **Mark follower loops with ‘#pragma ivdep’ in C code**
  - ‘ivdep’ tells the back-end compiler to ignore vector dependencies
    - each compiler has slightly different semantics for the pragma

- **‘ivdep’ permits back-end to ignore assumed dependencies**
  - iteration dependence, memory aliasing, etc.
  - back-end may unconditionally vectorize loops with potential aliases
    - instead of two loops with a runtime check to see if the vector version is safe
  - back-end can vectorize loops that it assumed were illegal before

Vectorization: This Effort (continued)

- **Compiler approach for marking follower loops with ivdep**
  - mark yielding follower loops as order-independent during resolution
    - these are the loops that will execute the body of a forall loop
    - (others may do bookkeeping unrelated to the loop's forall semantics)
  - propagate order-independence during iterator lowering/inlining
    - loops that cannot be inlined are not order-independent
      - advance() function cannot be vectorized
    - a zippered iterator is order-independent iff all iterands are & they are inlined
  - if vectorization is enabled, annotate these order-independent loops
    - generate CHPL_PRAGMA_IVDEP, defined in the runtime for each compiler

- **Added extensive test suite**
  - uses a reporting mechanism to ensure correct loops are annotated
    - and other loops are not mistakenly annotated

Vectorization: Impact

- **Many serial follower loops are annotated**

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

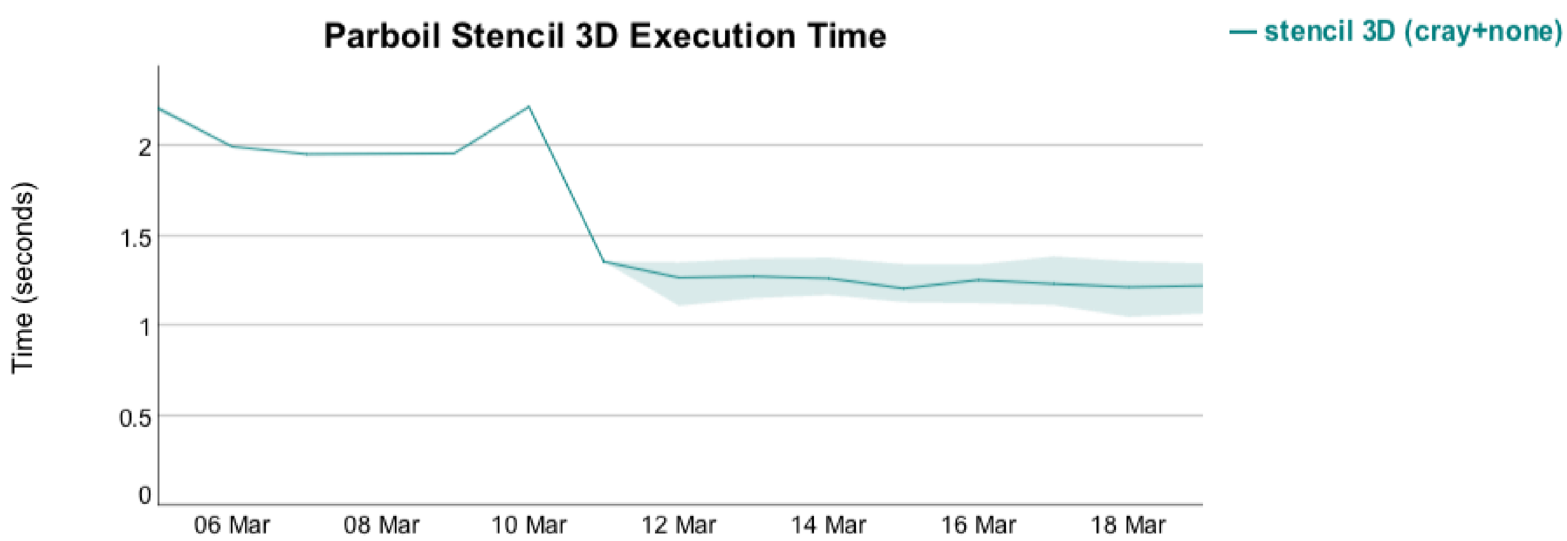
generates:

```
…
CHPL_PRAGMA_IVDEP
for (i = low; i <= high; i += INT64(1)) {
  call_tmp = (shiftedData + i);
  *(call_tmp) = i;
}
```

- **Improves vectorization of loops**
  - determined via back-end vectorization reporting output
    - fewer conditional checks at runtime
    - some previously non-vectorizable loops are now being vectorized

Vectorization: Impact (continued)

- **Performance improvements**
  - 20% performance improvement of stream-ep on Intel KNC
    - runtime checks were more expensive on KNC vs. Xeon
  - improvements for benchmarks with complex array access patterns



Vectorization: Status

- **Vectorization is enabled with the --vectorize flag**
  - automatically enabled with --fast
  - controls whether order-independent loops are marked with ivdep
    - will control more settings in the future (hence generic name)

- **Ran into issues with Cray as the back-end compiler**
  - ‘ivdep’ has slightly different semantics compared to other compilers
    - discovered late in release cycle
    - conservatively stopped annotating with ‘ivdep’ for Cray
    - additional work required to re-enable in appropriate cases

Vectorization: Related Next Steps

- **Add more loop and vectorization benchmarks**
  - Livermore Compiler Analysis Loop Suite (LCALS)
    - (formerly Livermore Loops)
- **Add tests to inspect back-end vectorization reports**
  - to detect which loops are actually being vectorized
- **Start performance testing on Xeon Phi**
- **Explore options with Cray compiler**
  - see what additional analysis we need to attach ‘ivdep’

Vectorization: Additional Next Steps

- **Align memory allocations and generate alignment hints**
  - eliminate loop peeling, cleaner vectorization
- **Mark non-aliasing pointers with ‘restrict’ keyword**
  - perform alias analysis at Chapel level and annotate restricted pointers
    - Chapel has limited aliasing, this helps convey that to the back-end
    - should help with vectorization and other performance optimizations
- **Investigate potential generated code improvements**
  - engage back-end compiler developers for recommendations
- **Explore what we can do with LLVM**
  - we may become constrained by what we can express in C
  - might be able to convey more Chapel semantics to LLVM back-end

Parallel Range Iteration Optimization

Parallel Range Optimization: Background

- **Discovered that parallel iteration over a range was slow**
  - dramatically slower than iterating over a 1-dimensional domain
    - surprising since the domain iterator forwards to a range iterator
    - unfortunate since we tend to advise “ranges are cheaper than 1D domains”
- **Range iterator is more complicated than domain iterator**
  - ranges have to support iteration over an unbounded space
- **Determined that range followers were not being inlined**
  - iterators need to be inlined for optimal performance
    - otherwise an expensive advance() function is called in every iteration
- **Also found that parallel zippered range iteration was slow**
  - zippered iterators have stricter inlining constraints

Parallel Range Optimization: This Effort

- **Update follower iterator so it can be directly inlined**
  - previous "optimization" for single-element ranges prevented inlining
- **Added a special case for non-stridable ranges**
  - non-stridable ranges now utilize a more optimized iterator
    - domain follower already had this optimization
- **Update follower so it can be inlined into zippered iterators**
  - early returns for length == 0 prevented inlining
    - tricky to work around, solution is fast but not elegant

Parallel Range Optimization: Code Impact

- **Range follower iterator can now be inlined in all cases**

  generated follower loop code for:

```
forall i in 1..10 do writeln(i);
```

  previously:

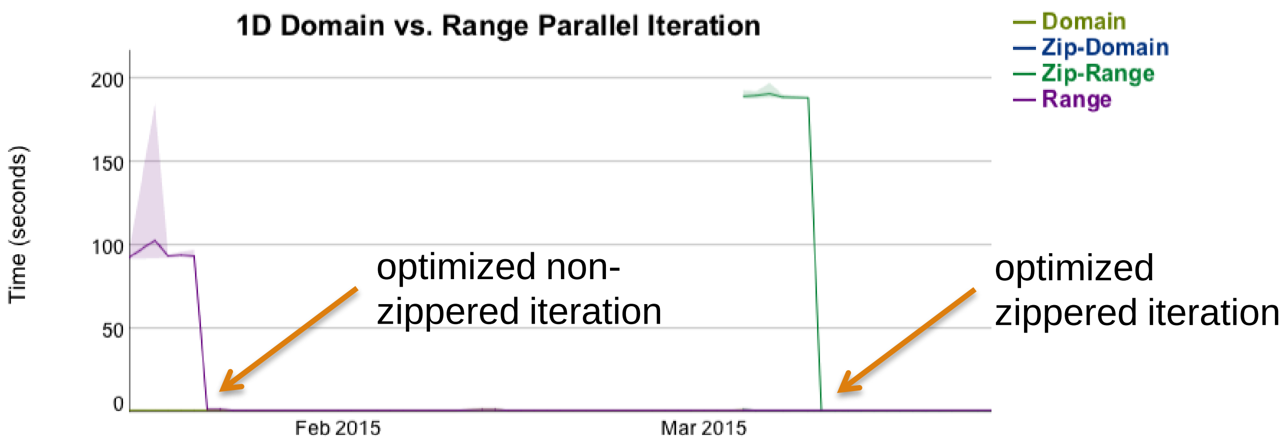
```
...
advance(_ic_);
for (; (T3 = (_ic_)->more,T3); ) {
  T2 = (_ic_)->value;
  writeln(T2);
  advance(_ic_);
}
```

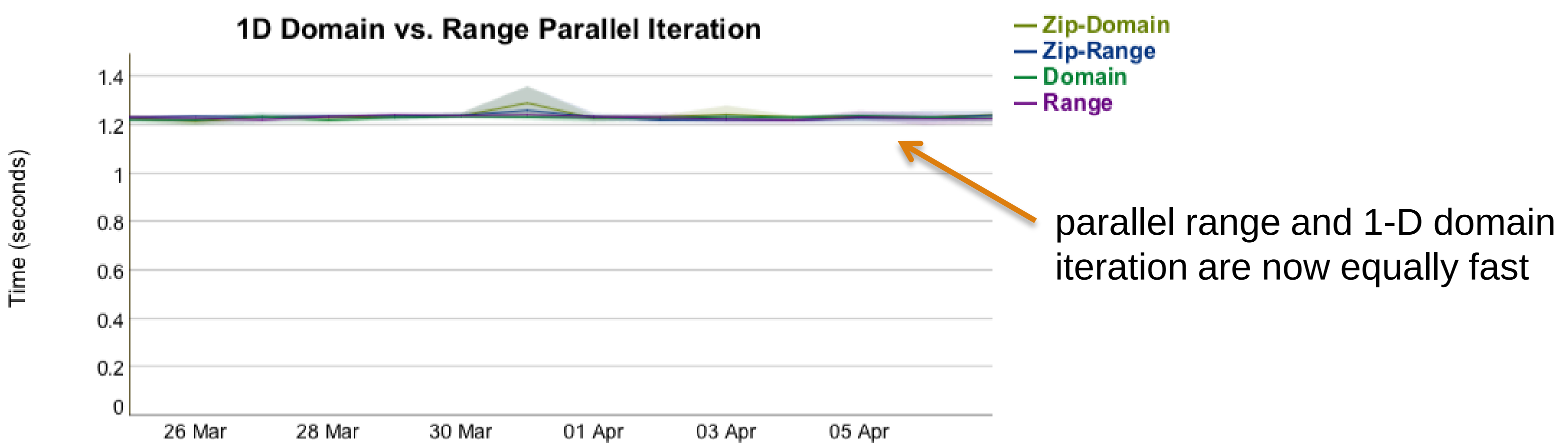
  now:

```
...
for (i = low; i <= end; i += INT64(1))
  writeln(i);
```

Parallel Range Optimization: Perf Impact

- Parallel range iteration is competitive with domains





Parallel Range Optimization: Next Steps

- **Add user-accessible documentation on iterator inlining**
  - guidelines for optimal iterator performance

- **Enhance iterator inlining reporting**
  - current reporting is limited and developer-focused
    - only reports iterators that were successfully inlined
  - want user-friendly reporting with specific reasons if inlining fails
  - could be part of a broader --performance-hints flag

- **Relax zippered iterator inlining constraints**
  - believed to be stricter than they need to be
    - likely part of upcoming “leader/follower 2.0” work

Loop-Invariant Code Motion (LICM) Update

LICM: Background

- **LICM hoists invariant code out of loop bodies**
  - may improve execution performance

```
for i in 1..10 { var t = 10 * someConst; } // can hoist t
```

- **LICM is performed on a per-function basis**
  - modifications to local variables are directly visible
    - through direct assignment or a function call (when passed by reference)

```
for i in 1..10 { local = i; f(local); var t = 10 * local; }
```

  - modifications to module-level variables may not be directly visible
    - e.g. through an arbitrary function call

```
for i in 1..10 { modifyGlobal(); var t = 10 * global; }
```

- **Stopped hoisting module-level variables for 1.10**
  - discovered that analysis for module-level variables was incorrect
  - resulted in performance regression for some variants of Fannkuch
    - only affected the slower versions, did not affect the fastest versions

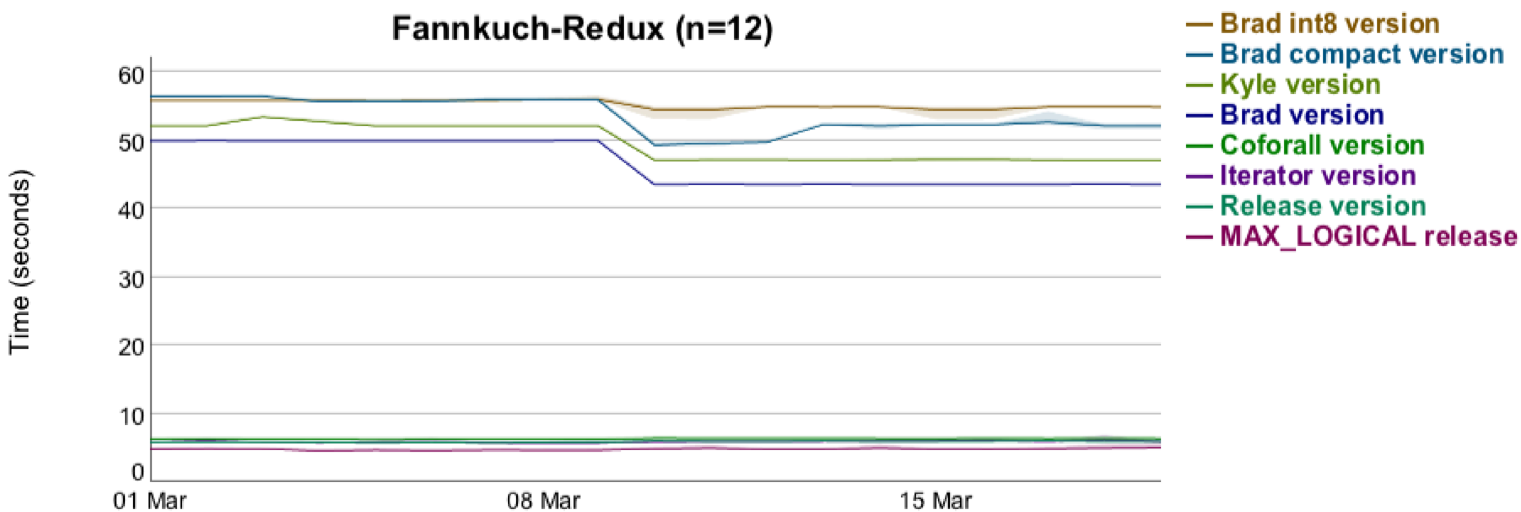
LICM: This Effort

- **Update analysis for module-level variables**
  - check if a loop contains any function calls
  - assume a function call will modify every module-level variable
    - conservative; but simple, cheap to compute, and handles most cases

- **Hoist module-level variables from loops w/o function calls**

LICM: Impact

- Resolved performance regression



- Improved communication counts for several tests

LICM: Next Steps

- **Could do limited interprocedural analysis**
  - instead of assuming function calls modify every module-level variable

- **LICM was not added as a traditional performance optimization**
  - introduced because array meta-data prevented offloading to accelerators
  - many opportunities to improve its analysis and capabilities
    - allow hoisting from loops that contain synchronization constructs
    - make alias analysis less conservative
    - do better analysis of argument intents
    - perform full interprocedural analysis

The “local field” pragma

Compile-time optimization to reduce communication overhead

Local fields: Background

- **Compiler conservatively inserts wide pointers**
  - This approach errs on the side of simplicity+correctness over speed
- **These calls introduce runtime overhead**
  - Structs are used to refer to remote memory
  - The compiler may refer to local memory through this struct

```
typedef struct {
  int localeID:
  void* memory;
} remoteThing;
```

```
int x = 0;
wide_x.localeID = here.id;
wide_x.memory = &x;
// when we want to read x
int local_x;
local_x = comm_get(wide_x);
```

  - Fortunately, the runtime will avoid communication for local memory

```
comm_get(src):
    if src.localeID == here.id :
        return *src.memory;
    else: actual runtime communication
```

Local fields: Background

- **The compiler always inserts communication for fields**
- **This is bad for the C pointers we use inside arrays**
  - Struct access overhead
  - Potential for communication thwarts back-end compiler optimizations
- **The 'local' block tends to save us in distributed code**

  Pros: fairly simple implementation with good performance results

  Cons: Imprecise; scoping issues; difficult to define precise semantics

```
proc dsiAccess(i : int) { // used to read array elements
  local {                 // asserts no comm required to reduce overheads
    if myLocalDomain.member(i) return myData[i];
  }
  // remote code…
}
```

Local fields: This Effort

- **Allow class designers to assert locality for fields**
  - Fine-grained, data-centric assertion
- **Approach: introduce a new pragma "local field"**
  - Only works for class fields within an aggregate type
  - Automatically applied to arrays in an aggregate type

```
class Foo {
  var x : int;
}
class Bar {
  pragma "local field"
  var f : Foo;
}
```

Local fields: This Effort

- **Applied this pragma to C pointers in DefaultRectangular**
  - DefaultRectangular is…
    …the domain map used to implement local arrays by default
    …also used as the guts of virtually every other domain map (e.g., Block)
  - Its pointers should never point to remote data
  - Represents a significant source of overhead given its widespread use

- **Runtime checks inserted to ensure correctness**
  - Invoked on reads or writes of such fields
  - Generates runtime error if field is assigned remote data
  - Can disable with "--no-local-checks"
    - Or with --no-checks or --fast

```
class Bar {
  pragma "local field"
  var f : Foo;
}
```

```
// should always return true
proc Bar.check() {
  return this.locale.id == this.f.locale.id;
}
```

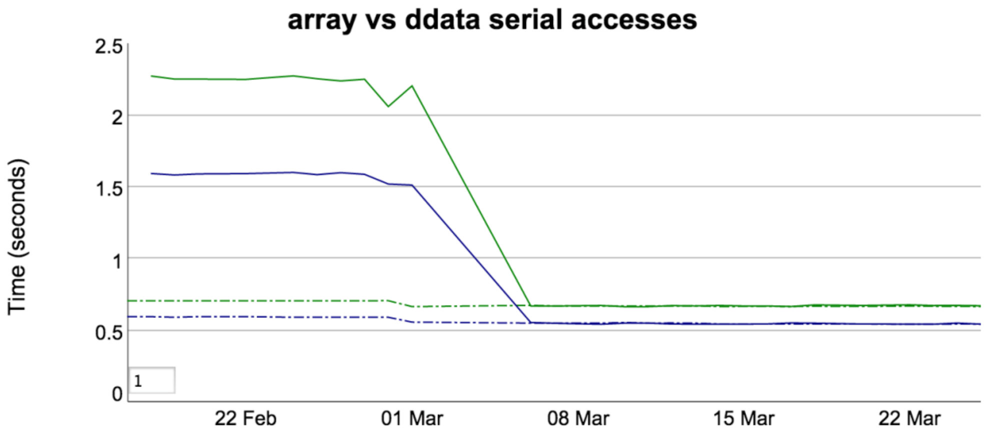
Local fields: Impact

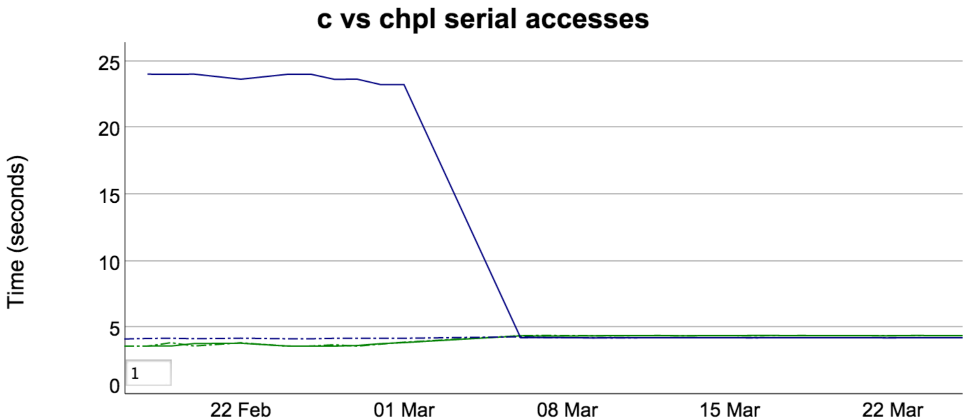
- **Reduced communication overhead for simple cases**

- **Most effective on programs without:**
  - Distributions
  - on-statements
  - local-blocks
  - User-defined classes or records (these don't have the pragma)

Local fields: Impact

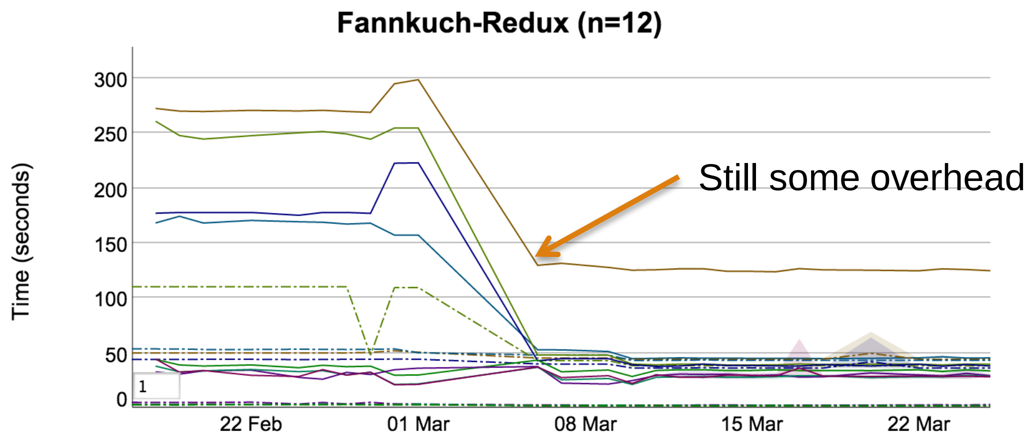
- **Some single-locale tests now have no --no-local overhead**
  - solid lines are --no-local compilations; dashed are --local

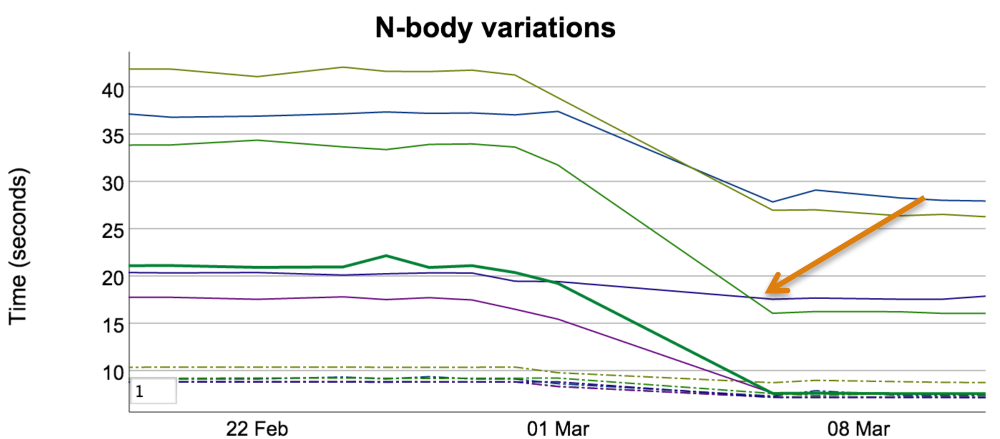




Local fields: Impact

- Other tests improved, but still have some overhead





Local fields: Status

- **Available in the 1.11 release**

- **Only used explicitly in DefaultRectangular**
  - May be applied elsewhere
  - Automatically applied to arrays in aggregate types
    - Based on Chapel semantics
    - These should always match the containing object's locale

- **Little impact on real distributed codes**
  - e.g., HPCC, SSCA#2
  - Use of 'local' blocks was likely eliminating overhead in kernels already
    - Future work: remove local blocks without affecting performance

Local fields: Next Steps

- **This data-centric notion of locality is valuable**

- **Replace pragma with a robust language-level construct**
  - Not just fields
    - Array elements
    - Regularly-scoped variables
    - Arguments? Returned variables?
  - Still in design phase
    - But here's an idea:

```
var baz : local Foo;

var data : [1..10] local Foo;

// Instead of a pragma…
class Bar {
  var f : local Foo;
}
```

Local fields: Next steps

- **Deprecate the 'local' block**
  - This statement is imprecise
  - Scoping rules limit its applicability
  - We would prefer finer-grained, data-centric locality assertions

- **Support Local Array Views**
  - Often a program wants to only work with local array data
    - typically results in similarly conservative "is this element remote?" checks
  - Doing so today is possible, but a bit clunky
  - Sketch of concept:

```
var myLocArrElts = Arr[local];
…myLocArrElts[i,j]…      // fast local access to A[i,j]; OOB if (i,j) is remote
```

  - Current array-view effort provides a framework for this feature

Local Fields: Next steps

- **Given "`on foo do …`"**

- **Avoid on-statement overhead**
  - If `foo` is local, we can avoid runtime overhead for on-statements
  - Namely, avoid allocating bundled arguments
    - This is important for atomic operations, which have on-statements

- **Optimize `foo` within the on-statement**
  - By definition, the on-statement will execute on `foo`'s locale
  - Thus, we know references to `foo` are local within the on-statement

Local Fields: Next steps

- **Determine other opportunities for optimization**
  - Distributed inner loops
  - Function specialization (create local and non-local versions)

The “assertNoSlicing” config param

Avoiding unnecessary multiplication for array accesses

assertNoSlicing: Background

- **Chapel uses a multiplication per dim for each array access**
  - Used to support rich array views: strided slicing, rank-change
  - In most common cases, multiplier for innermost dimension is 1
    - therefore, wasted math

- **These extra multiplications can hurt performance**
  - Particularly compared to C, which never requires such multiplications
  - For memory-bound code, typically a wash
    - e.g., STREAM Triad
  - For codes tuned for the memory hierarchy, can hurt performance
    - e.g., CSU's tiled iterator study for their ICS paper

assertNoSlicing

This Effort:

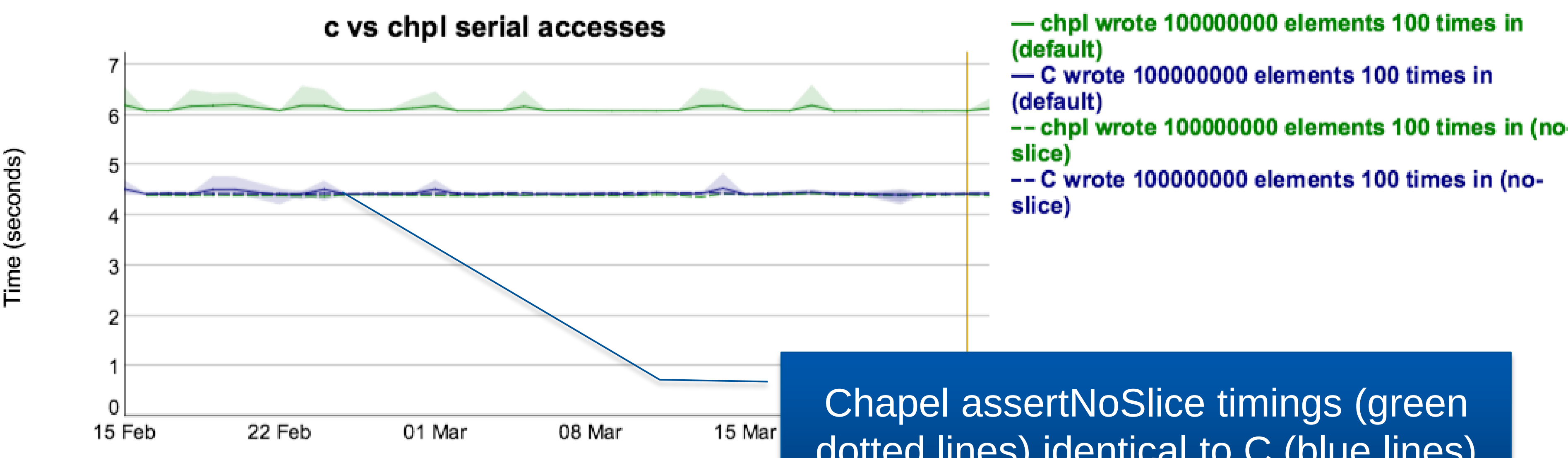
- As a stopgap, add a knob that lets users assert no such mults needed
  - This is a program-wide assertion about every array (so, a big hammer)

    ```
    chpl foo.chpl -sassertNoSlicing
    ```
- This squashes the extra multiplication for all array accesses
- If slicing does occur, the program may have errors
  - e.g., seg faults, incorrect results

assertNoSlicing: Performance improvements

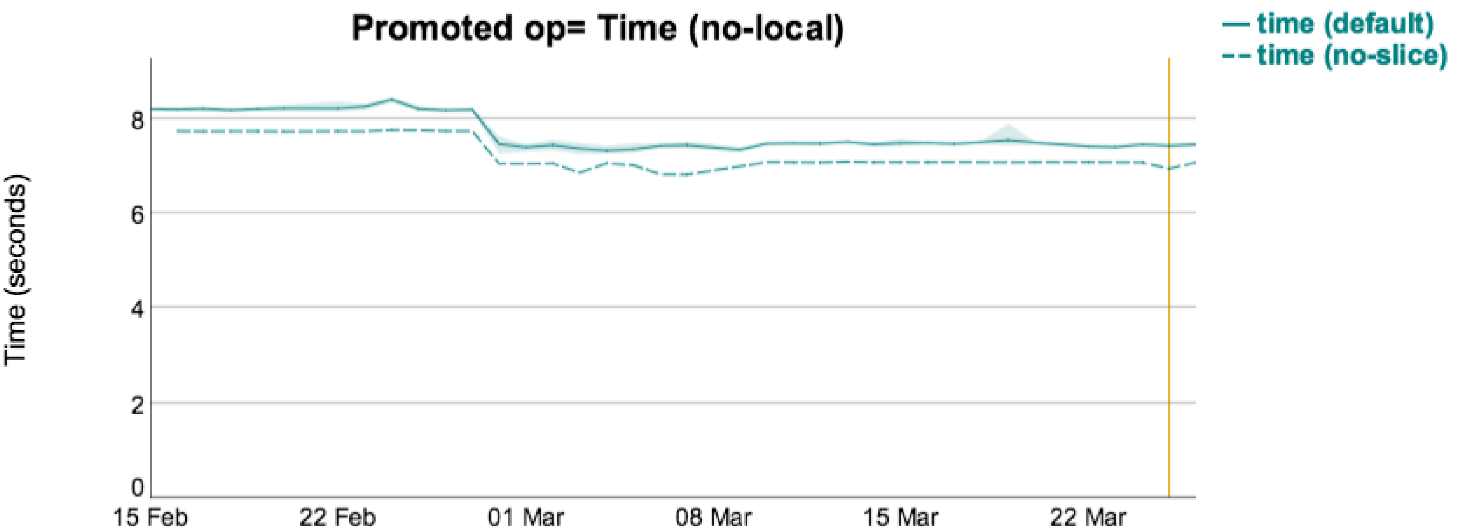
Impact:

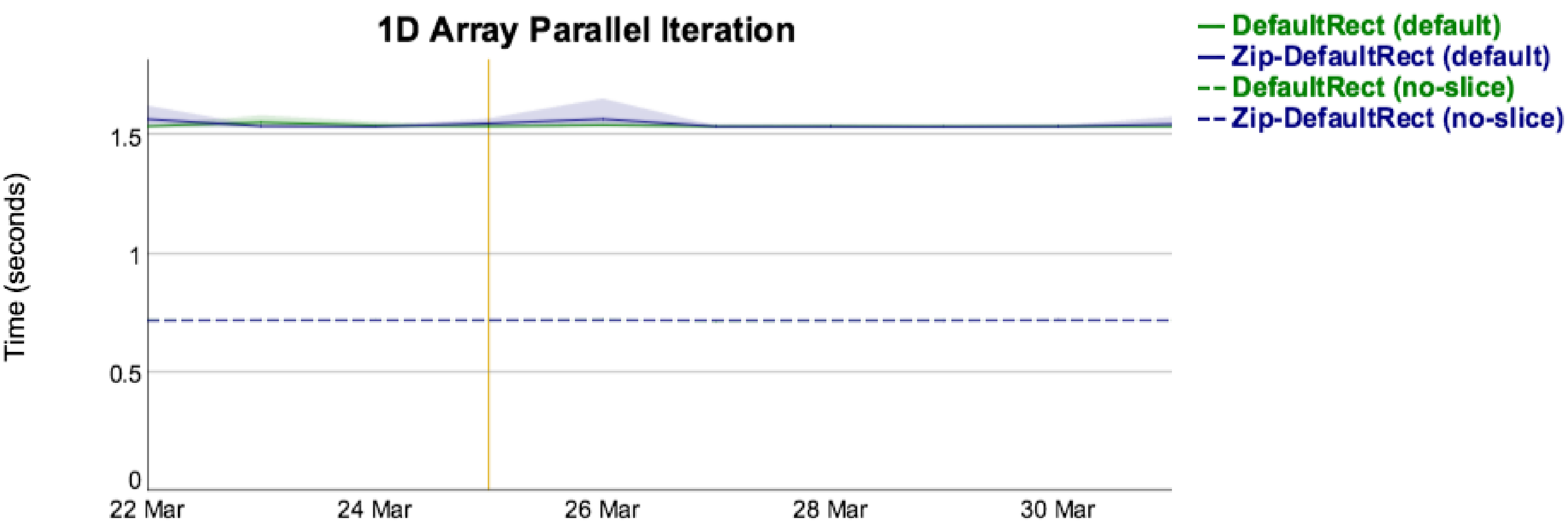
- Performance improvements seen in computationally intensive tests
- Nearly the same as C array performance



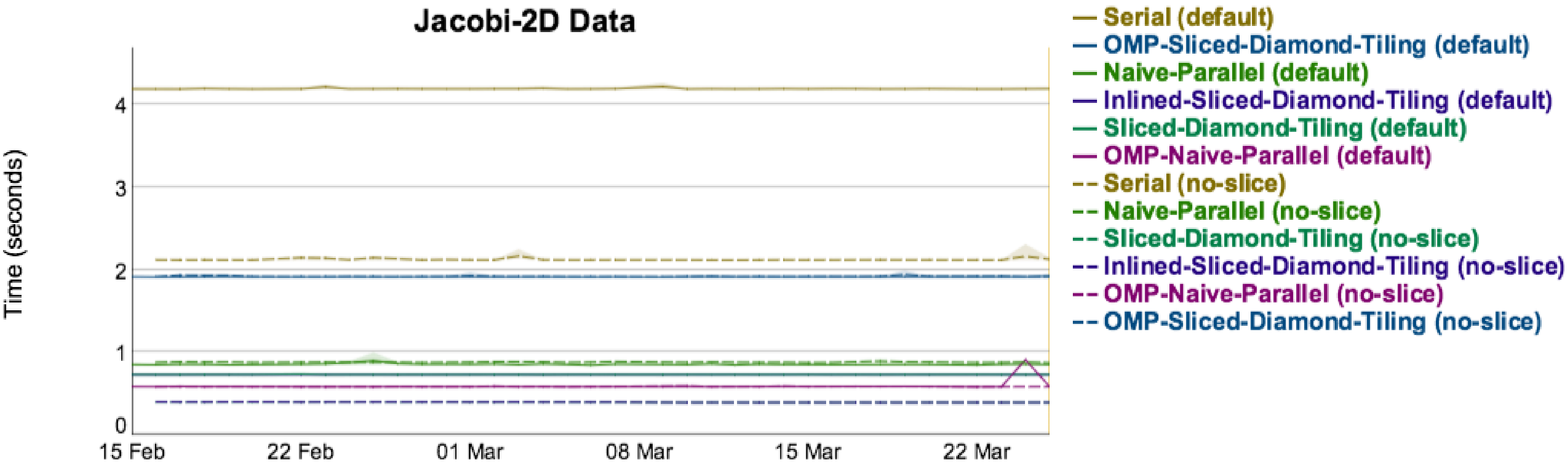
Chapel assertNoSlice timings (green dotted lines) identical to C (blue lines)

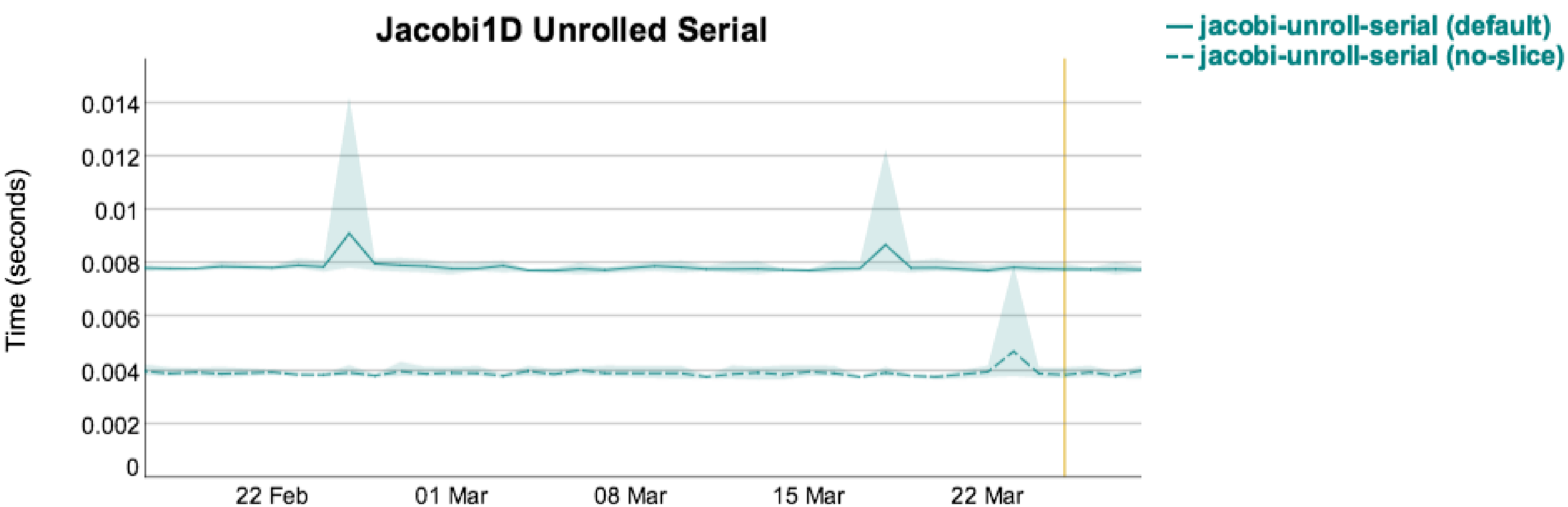
assertNoSlicing: Other Array Idioms





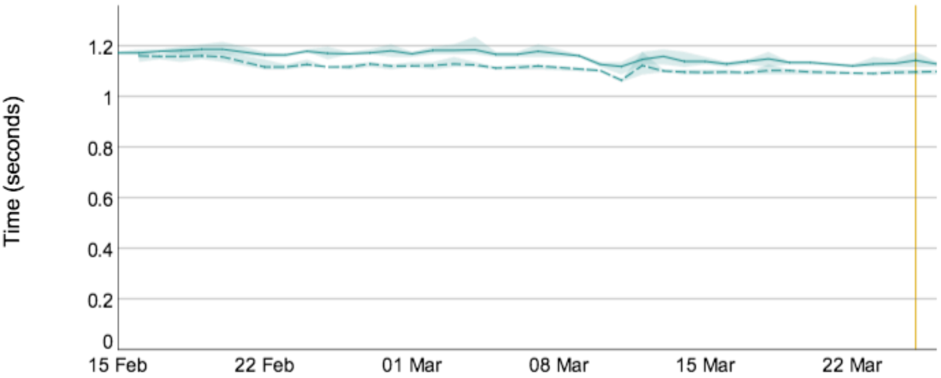
assertNoSlicing: Colorado State Benchmarks



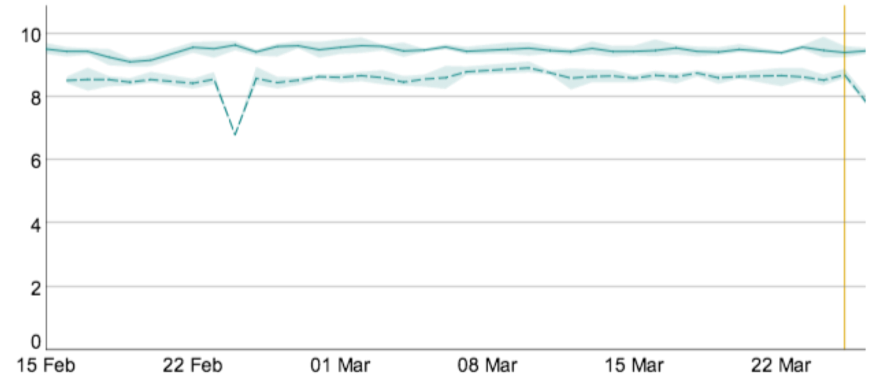


assertNoSlicing: Other Benchmarks

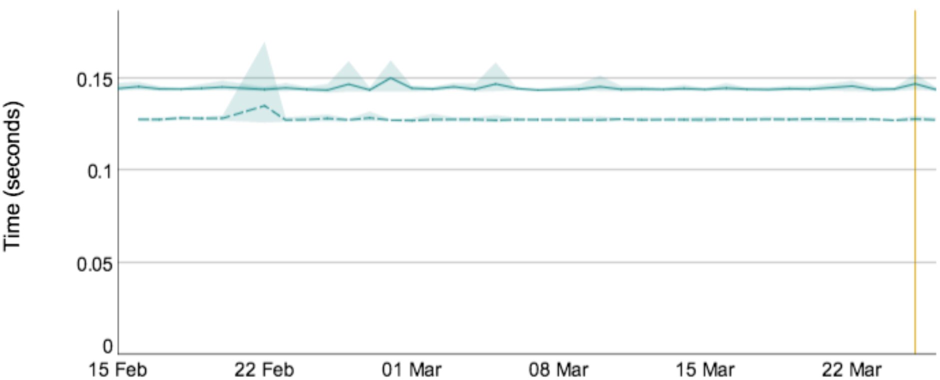
Reverse-complement Shootout Benchmark



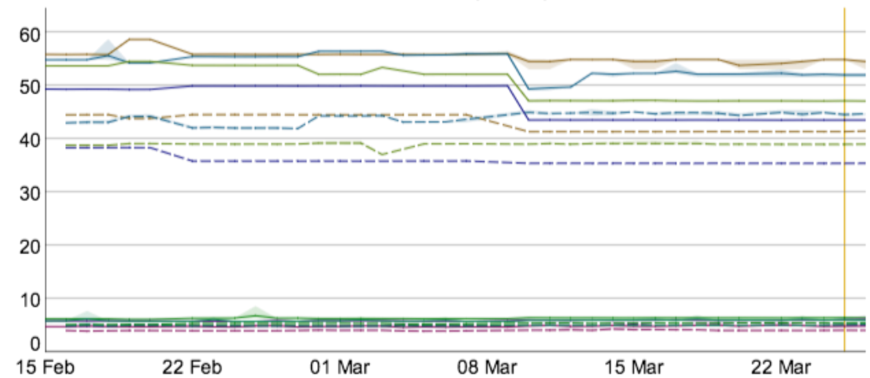
NAS Parallel Benchmarks: FT timings - size A



Parboil SAD Serial Execution Time



Fannkuch-Redux (n=12)



assertNoSlicing

Status: Off by default

- Must be for correctness w.r.t. advanced slicing/rank change operations
- Documented in the $CHPL_HOME/PERFORMANCE file

Next Steps:

- Automatically optimize away these multiplications
  - Effort currently underway as part of “array-view” domain map effort

External Procedures with ‘string’ Arguments

Extern procs with ‘string’ args: Background

Background:

- Some extern functions use line/filename info for error messages
  - They tend to expect an integer and a string

```
void proc foo(..., int line, char* filename);
```

- Such functions should be prototyped in Chapel as:

```
extern proc foo(..., line : c_int, filename: c_string);
```

…yet we were prototyping the filename argument as (Chapel) `string`
  - This works out because historically Chapel strings have been char*’s

- However, it resulted in memory leaks
  - String literal actuals were converted to Chapel strings, then never free’d

- Extern functions shouldn’t be passed Chapel strings anyway
  - The “string” internals are intended to be opaque

Extern procs with ‘string’ args: This Effort

This Effort:

- Fixed existing mismatched extern string/c_string arguments
- Added a compile-time error for extern prototypes taking string args
  - e.g., we now generate an error for:

```
extern proc foo(..., filename: c_string);
```

Impact: Less memory leaked

- Particularly beneficial for the internal NetworkAtomics module

Other Performance Improvements

Other Performance Improvements

- **Reduced overhead of module-scope variable references that are known to be local**
  - (in the "locality" sense, not the "lexical scoping" sense)
- **Localized additional remote variable references**
  - Reduced conservative widening of references that "may be remote"
- **Reduced memory leaks due to compilerWarning()s**
- **Avoided creating singleton tasks for serial scopes**
  - described in runtime deck

Optimization/Codegen Priorities and Next Steps

Opt/Codegen Priorities and Next Steps

- **Complete LCALS port and evaluate Chapel vectorization**
  - success/failure of Chapel vectorization compared to reference
  - performance of vectorized Chapel loops compared to reference
  - improve support if significant gaps exist
- **Continue locality optimization effort**
  - replace 'local' block with data-centric alternatives
    - 'local class' type annotations
    - local array view capability
  - optimize on-clauses
- **Automatically squash inner-dimension multiplications**
  - and deprecate –sassertNoSlicing config
- **Continue reducing size/complexity of generated code**
  - correlates to time spent in compilation

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