Performance Optimizations
Generated Code Improvements

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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
    
    ```csharp
    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 \( \leq \) or \( \geq \) rather than \( \neq \)
    - (OpenMP/OpenACC pragmas can't be attached to loops terminated by \( \neq \))
  - 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

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

previously:

```haskell
 BuildRange(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:

```haskell
for (i = INT64(1); i <= INT64(10); i += INT64(1))
    writeln(i);
```
Optimized iteration for strides known at compile time

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

Previously:

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

Now:

```plaintext
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

```plaintext
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

```plaintext
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
    \[ \text{forall } i \text{ in } 1..10 \text{ do } \ldots \]

● 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
    
    \[ A = B + C; \]
    \[ \text{forall } i \in 1..n \text{ do } A[i] = B[i] + C[i]; \]
    \[ \text{forall } (a, b, c) \in \text{zip}(A, B, C) \text{ do } a = b + c; \]

● **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

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

generates:

```plaintext
...
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

![Parboil Stencil 3D Execution Time](image-url)
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:

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

  previously:

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

  now:

  ```pascal
  ...
  for (i = low; i <= end; i += INT64(1))
    writeln(i);
  ```
Parallel Range Optimization: Perf Impact

- Parallel range iteration is competitive with domains

1D Domain vs. Range Parallel Iteration

- Optimized non-zippered iteration
- Optimized zippered iteration

1D Domain vs. Range Parallel Iteration

- Parallel range and 1-D domain iteration are now equally fast
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

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

```c
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

```c
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

```plaintext
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

```c
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

```java
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

![Graph 1: Array vs ddata serial accesses](image1)

![Graph 2: C vs CHPL serial accesses](image2)
Local fields: Impact

- Other tests improved, but still have some overhead

![Graph showing Fannkuch-Redux (n=12) and N-body variations with time (seconds) on the y-axis and dates on the x-axis, indicating a decrease in time with some overhead.](image-url)
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:

```plaintext
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:
    ```javascript
    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

Promoted op= Time (no-local)

1D Array Parallel Iteration
assertNoSlicing: Colorado State Benchmarks

Jacobi-2D Data

Serial (default)
OMP-Sliced-Diamond-Tiling (default)
Naive-Parallel (default)
Inlined-Sliced-Diamond-Tiling (default)
Sliced-Diamond-Tiling (default)
OMP-Naive-Parallel (default)
Serial (no-slice)
Naive-Parallel (no-slice)
Sliced-Diamond-Tiling (no-slice)
Inlined-Sliced-Diamond-Tiling (no-slice)
OMP-Naive-Parallel (no-slice)
OMP-Sliced-Diamond-Tiling (no-slice)

Jacobi1D Unrolled Serial

jaci-unroll-serial (default)
jaci-unroll-serial (no-slice)
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

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

- Such functions should be prototyped in Chapel as:

```chapel
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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