Vectorization of Chapel Code

Elliot Ronaghan, Cray Inc.

CHIUW @PLDI

June 13, 2015

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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)

- **Several recent efforts to help the back-end vectorize:**
  - Generate Chapel for-loops as C for-loops
  - Optimize anonymous range iteration
  - Annotate data parallel loops with vectorization pragmas
  - Currently exploring manual marking of vectorizable loops

C for-loops: Background

- **Chapel for-loops and C for-loops are different**
  - Chapel for-loops invoke iterators or iterate over data structures:

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

  - C for-loops are a specialized while-loop with init and incr clauses:

    ```
    for (i=1; i<=10; i+=1) …
    ```

  - Chapel for-loops are more powerful:

    ```
    for a in myArray do …
    for (a, j) in zip(myArray, 1..10) do …
    ```

- **Want Chapel for-loops to be generated as C for-loops**
  - this is the form back-end compilers are designed to optimize
  - required for attaching vectorization annotations
  - will result in clean and readable generated code

C for-loops: Background (continued)

- **Most for-loops are driven by ranges**
  - they either directly iterate over range
  - or a structure whose iterator forwards to a range iterator
    - e.g. arrays, distributions

```
for a in myArray do …              // iterate over an array
```

…is implemeted in terms of…

```
array.these() {
  for i in myDomain do             // array iterates over its domain
    yield dsiAccess(i);
}
```

…which is implemented in terms of…

```
domain.these() {
  for i in myRange do              // domain iterates over its range(s)
    yield i;
}
```

C for-loops: Background (continued)

- **Range iterators traditionally generated C while-loops**

```
for i in 1..10 do …                 // range iteration
```

generated:

```
i = first;
end = last + 1;
cont = (i != end);
while(cont) {                       // generated while loop
  tmp = (i+1);
  i = tmp;
  cont = (tmp != end);              // != relational operator
}
```

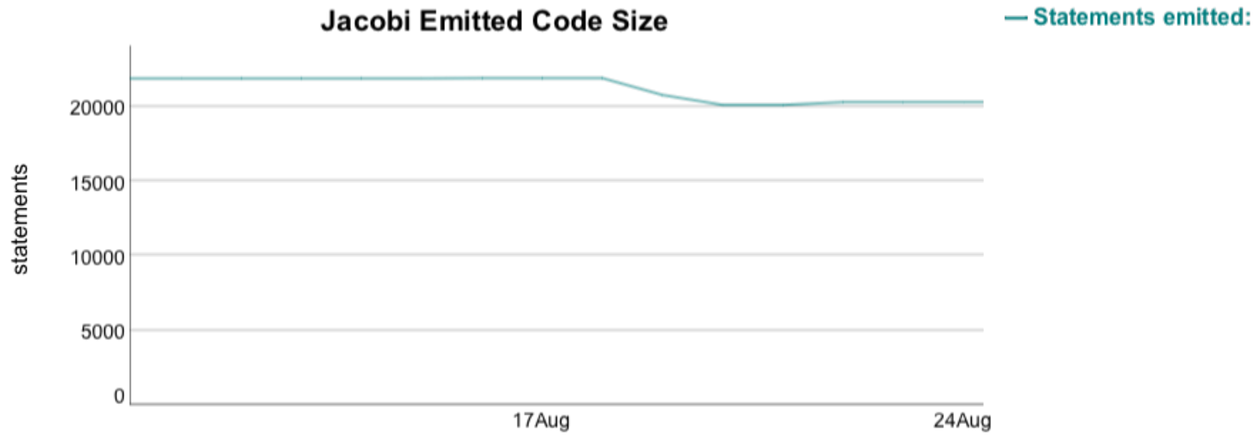
- not a loop that back-end compilers are designed to optimize
- not amenable to auto-vectorization or vectorization pragmas

C for-loops: This Effort

- **To generate most Chapel for-loops as C for-loops we now:**
  - generate range iterators using C for-loops
    - results in iterators that forward to ranges being generated as C for-loops
  - generate zippered iterators as C for-loops
    - because iterator inlining/lowering process is different for zippered iterators

C for-loops: Impact

- **Generated code improvements**
  - Decreased generated code size: ~22,000 => ~20,500 for Jacobi



  - Improved readability of generated code

```
for i in 1..10 do …
```

generates:

```
for (i = start; (i <= end); i += INT64(1))
```

C for-loops: Impact (continued)

- **Generated code for range iteration**

```
for i in 1..10 do …
```

previously:

```
i = start;
end = last + 1;
cont = (i != end);
while (cont) {
  tmp = (i+1);
  i = tmp;
  conttmp = (tmp != end);
  cont = conttmp;
}
```

now:

```
for (i = start; (i <= end); i += INT64(1))
```

C for-loops: Impact (continued)

- **Generated code for zippered array iteration**

```
for (a, b) in zip(A, B)
```

previously:

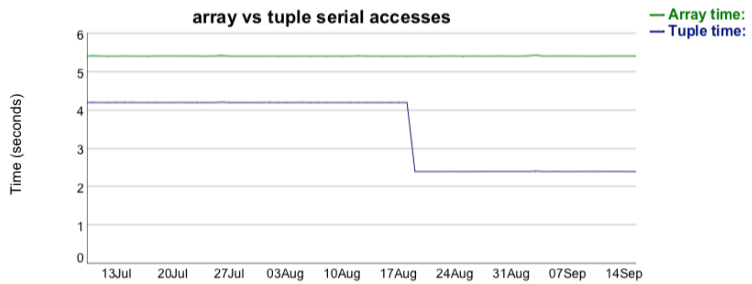
```
 for (;_cond;) {
    _ref_tmp_5 = &_ic__F6_i;
    *(_ref_tmp_5) += _ic__F4_step;
    tmp31 = (_ic__F6_i != _ic__F5_last);
    if (tmp31)
      _ic__more = INT64(1);
     else
      _ic__more = INT64(0);
    _cond = (_ic__more != INT64(0));
    _ref_tmp_6 = &_ic__F6_i2;
    *(_ref_tmp_6) += _ic__F4_step2;
}
```

now:

```
for (_ic_i = start1, _ic_i2 = start2;
(_ic_i <= _ic_last); ic_i += _ic_step, _ic_i2 += _ic_step2)
```

C for-loops: Impact (continued)

- **Performance Improvements**
  - not many changes in our nightly performance testing
    - couple cases like serial tuple accesses



  - however, we believe there are real world performance improvements
    - our nightly testing uses gcc 4.7
    - it seems to lack some optimizations that benefit from C for-loops
  - performed manual testing using gcc 4.9, intel, and cray compilers
    - used stream and simple vector addition
    - showed > 25% performance improvement in some cases
    - back-end compiler tools indicate more auto-vectorization occurring

C for-loops: Summary

- **Most Chapel for-loops now generate clean C for-loops**
  - However, previous generated code excluded range construction

```
for i in 1..10 do …
```

actually generates:

```
build_range(INT64(1), INT64(10), range);
start = range->low;
end = range->high;
for (i = start; i <= end; i += INT64(1))
```

- Want to eliminate construction when possible
  - such as when iterating over anonymous ranges

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
  - 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
  - allow back-end compiler to better optimize and auto-vectorize

- **This 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), range);
start = range->low;
end = range->high;
for (i = start; i <= end; 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
for (i = start; i != end; i += str)  // finally iterate, but using !=
  writeln(i);
```

71 SLOC

now:

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

Anonymous Range Opt: Impact (continued)

- **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
    - still 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
  ```

Anonymous Range Opt: Summary

- **Most Chapel for-loops generate "ideal" C for-loop equivalent**

- **Can now focus on conveying Chapel semantics to back-end**
  - Remember that Chapel is well-suited for vectorization because
    - limited aliasing
    - support for array programing

      ```
      A = B + C;
      ```

    - parallelism, and especially data parallelism is a first class concept

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

Data-par vectorization: Background

- **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**
  - 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

Data-par 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

Data-par 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

Data-par vectorization: Impact

- **Many serial follower loops are annotated**

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

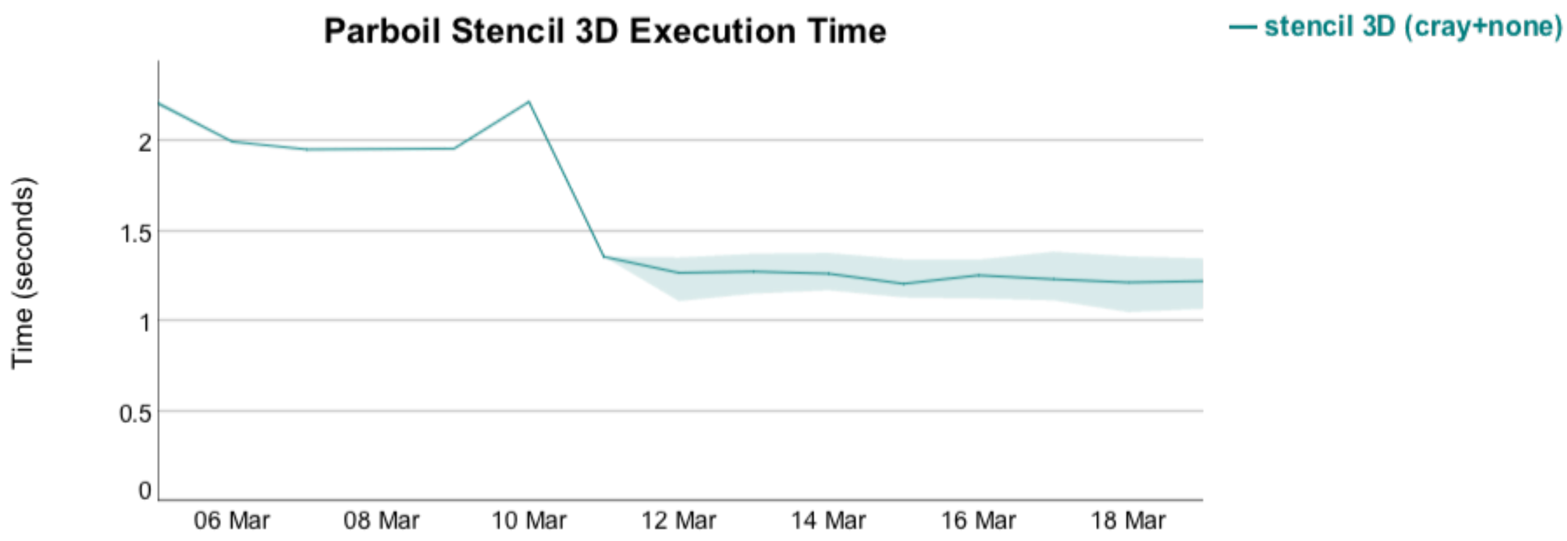
generates:

```
//~15 lines of follower setup
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

Data-par 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



Data-par 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

Data-par vectorization: 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 nightly performance testing on Xeon Phi**
- **Explore options with Cray compiler**
  - see what additional analysis we need to attach 'ivdep'

Data-par vectorization: Summary

- Many serial follower loops are annotated
- Improved vectorization of loops

Vectorization: Combined Impact

- Combined, these efforts greatly improve vectorization of Chapel code

```
forall i in 1..10 do …
```

1.9:

```
// ~75 lines of follower setup …
_build_range(fol.low, fol.high, &folRange);
// 4 fn calls to un-densify follower
_build_range(undenLow, undenHigh, &undenRange);
// 2 fn calls and conditional to compute start/end
while (test) {…}
```

102 SLOC

now:

```
// ~15 lines of follower setup …
low = fol.low, high = fol.high;
CHPL_PRAGMA_IVDEP
for (i = low; i <= high; i += INT64(1)) {…}
```

Vectorization: Next Steps

- **Let users provide vectorization hints on serial loops**
  - currently being worked on

```
for i in vectorizedIter(1..10) do …
```

- **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
- **Continue exploring other languages vectorization stories**
  - Does anyone have a good story?
    - Fortran? Julia? Intel’s ISPC?

Vectorization: Potential Next Steps

- **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
- **Explore users need for more explicit vectorization support**
  - do we need to provide explicitly vectorized data structures & libraries?

Vectorization: Closing Thoughts

- **Vectorization has greatly improved with recent releases**
  - with no user code changes required
- **That said, we still plenty of work to do**
  - with several improvements already in the pipeline
- **We are extremely interested in any user feedback**
  - about our current and future vectorization roadmap
  - and about other programming models with good vectorization stories

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