Vectorization of Chapel Code

Elliot Ronaghan, Cray Inc.
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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 programming
    \[
    A = B + C;
    \]
  - 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)

- 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
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
    ```c
    for a in myArray do ... // iterate over an array
    ...
    ...
    for i in myDomain do      // array iterates over its domain
      yield dsiAccess(i);
    }
    ...
    ...
    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

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

generated:

i = first;
end = last + 1;
cont = (i != end);
while(cont) {
  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: \(~22,000 \Rightarrow \sim 20,500\) for Jacobi

![Graph showing Jacobi emitted code size]

● Improved readability of generated code
  
  \[
  \text{for } i \text{ in } 1..10 \text{ do } ...
  \]

  generates:

  \[
  \text{for } (i = \text{start}; (i \leq \text{end}); i += \text{INT64}(1))
  \]
C for-loops: Impact (continued)

- Generated code for range iteration

```c
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)
```
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

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

  actually generates:

  ```c
  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
    ```python
    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

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

previously:

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

now:

```pascal
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

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

previously:

```pascal
// 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);
```

now:

```pascal
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

```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**
  
  ```pascal
  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

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

- **Data-parallelism implemented in terms of task-parallelism**
  - 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

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

generates:

```cpp
//~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

![Parboil Stencil 3D Execution Time](chart)

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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

```chapel
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) {...}
```

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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