Y.A.S.K.

Yet Another Stencil Kernel

Chuck Yount, Principal Engineer
Intel Corporation

April 14, 2016

chuck.yount@intel.com

Legal Disclaimer & Optimization Notice

Outline

Overview

YASK Features

- Vector folding and the fold builder
- Loop-code generator
- Memory accessor
- Debug output

Using YASK

- Build and test
- Output
- Use model
- Run-time options
- Stencil, vectorization, loop, and advanced customization
- Collaboration

Overview

YASK: Yet Another Stencil Kernel

- Goal: facilitate exploration of the stencil-performance design space for Intel® Xeon Phi™ coprocessor or any Intel processor supporting the AVX-512 instruction set

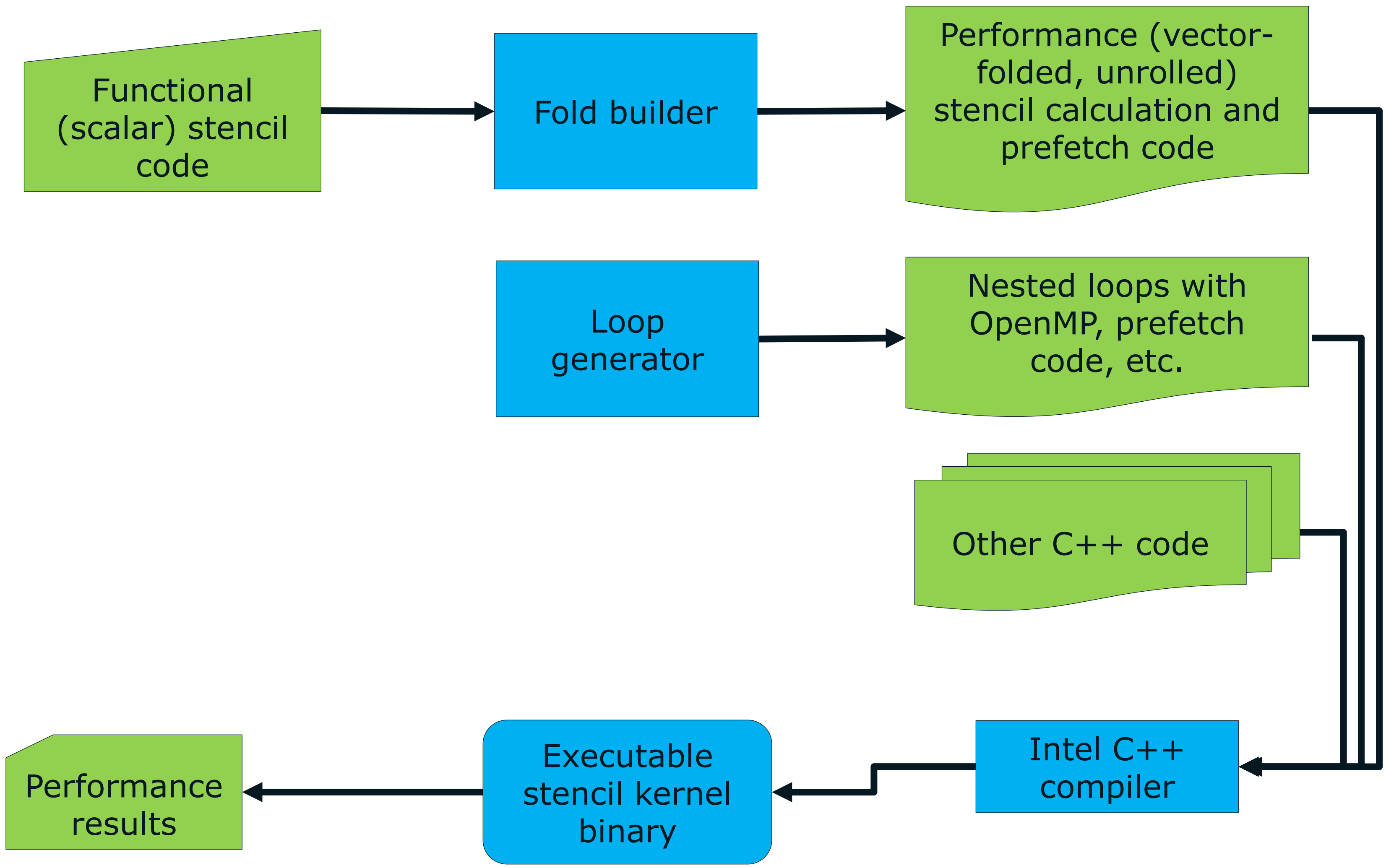
Features

- Supports trade-off studies for coding options for
  - Vector-folding
  - Cache blocking
  - Memory layout
  - Loop construction
  - And more
- Is a collection of C++ code, code-generators and other scripts
- Focused on single-node OpenMP optimizations (not MPI enabled at this time)

See also the related iso3dfd kernel (by Leo B, Cedric A, Philippe T)

YASK Features

High-level components



Vector-folding introduction

Concept

- Store small 2D or 3D block of data into each vector
- Pros: reduces memory BW requirements compared to traditional 1D in-line vectors
- Cons: requires data pre-conditioning (element rearranging) and additional shift and blend operations preceding SIMD arithmetic operations

Results

- Significant speedup shown on Intel® Xeon Phi™ Coprocessor
- Combining with loop tiling enables even more speedup

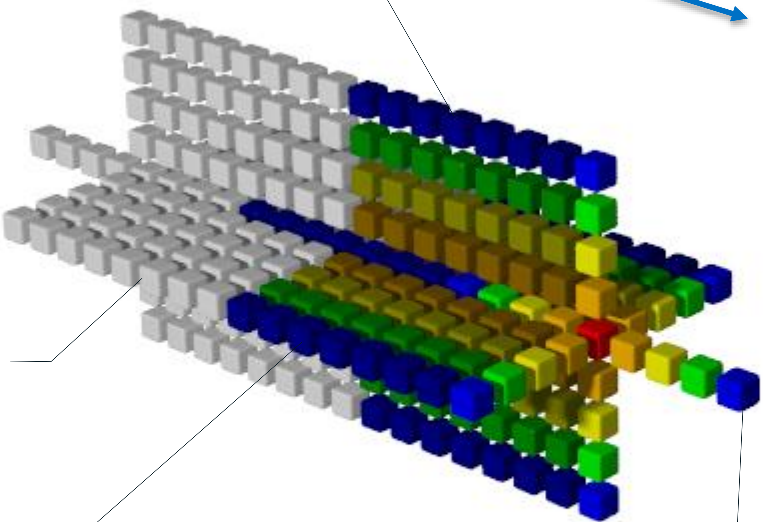
For more information

- Refer to paper on [Vector Folding from HPCC 2015]

Traditional in-line 1D vectorization

25-point 3D stencil input vectorized using 8-element vectors, each parallel to x-axis

Inner 3D loop iterates in x direction, i.e., *same dimension* as vectorization



Previous iteration

Current iteration

Need to read 17 new cache lines* for each iteration (8 of the 25 vectors overlap in x dimension)

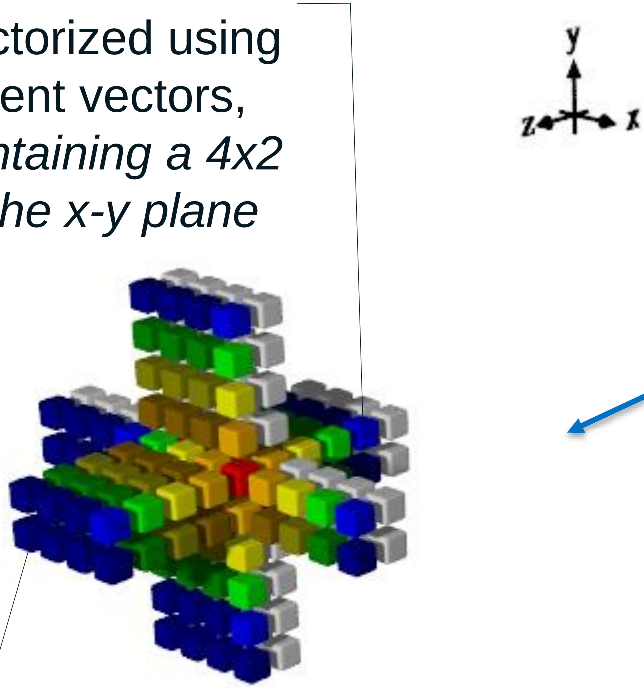
One 8-element vector output per iteration

Steady-state memory BW = **17** new cache lines input to calculate each vector of output

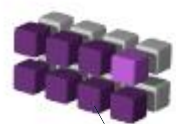
*Assuming cache line size = vector size.

Reduce BW via vector folding

25-point 3D stencil input vectorized using 8-element vectors, *each containing a 4x2 grid in the x-y plane*



Inner 3D loop iterates in z direction, i.e., *perpendicular* to 2D vector



One 8-element (4x2) vector output per iteration

Need to read only 7 new cache lines for each iteration (vectors overlap in x-y dimensions within an iteration and in z dimension between iterations)

Steady-state memory BW = **7** new cache lines input to calculate each vector of output: **2.4x lower** than in-line

Fold-builder code generator

Goal: automate the tedious and error-prone process of creating high-performance stencil code

Input

- Inherit from a C++ abstract 'StencilBase' class to create a new stencil type
- Define the grid(s) to be used and the names of their dimensions, e.g., "t", "x", "y", "z"
- Implement the 'define' method to define how one point in each grid is calculated from others
- Use loops, functions for coefficients, recursion, etc.

Process

- Compile code into fold-builder executable
- Run executable, specifying any stencil parameters (e.g., order), target architecture, etc.
- Code generator evaluates the 'define' method to create an abstract syntax tree (AST)
- AST is traversed, and optimized code is output

Output

- Efficient function to calculate stencil
  - Unrolled loops, intrinsics to construct unaligned vectors of points, etc.
  - Calls to memory accessor object
- Functions for prefetching to L1 and L2

Example input stencil code

```
 INIT_GRID_4D(pressure, t, x, y, z),
 INIT_GRID_3D(vel, x, y, z)
…
 virtual void define(const IntTuple& offsets) {
…
        // start with center value multiplied by coeff 0.
        GridValue v = pressure(t, x, y, z) * coeff(0);

        // add values from x, y, and z axes multiplied by the
        // coeff for the given radius.
        for (int r = 1; r <= _order/2; r++) {

            // Add values from axes at radius r.
            v += (
                  // x-axis.
                  pressure(t, x-r, y, z) +
                  pressure(t, x+r, y, z) +

                  // y-axis.
                  pressure(t, x, y-r, z) +
                  pressure(t, x, y+r, z) +

                  // z-axis.
                  pressure(t, x, y, z-r) +
                  pressure(t, x, y, z+r)

                  ) * coeff(r);
        }

        // finish equation, including t-1 and velocity components.
        v = (2.0 * pressure(t, x, y, z))
            - pressure(t-1, x, y, z) // subtract pressure from t-1.
            + (v * vel(x, y, z));       // add v * velocity.

        // define the value at t+1 to be equivalent to v.
        pressure(t+1, x, y, z) == v;
    }
```

Define 2 grids: 4D "pressure" and 3D "vel"

The final equation uses "==" in a declarative (not imperative) style

Example output stencil code

```
class Stencil_pressure {
...
void calc_vector(StencilContext& context, idx_t tv, idx_t xv, idx_t yv,
idx_t zv) {
...
 // Read aligned vector block from pressure at t, x, y, z.
 realv temp_vec2 = context.pressure->readVecNorm(tv, xv, yv, zv);
...
 // Construct unaligned vector block from pressure at t, x, y-1, z.
...
 realv_permute2(temp_vec8, ctrl_n, temp_vec7, temp_vec2);
...
 // Write aligned vector block to pressure at t+1, x, y, z.
 context.pressure->writeVecNorm(temp_vec63, tv+(1/1), xv, yv, zv);
 }
...
}
```

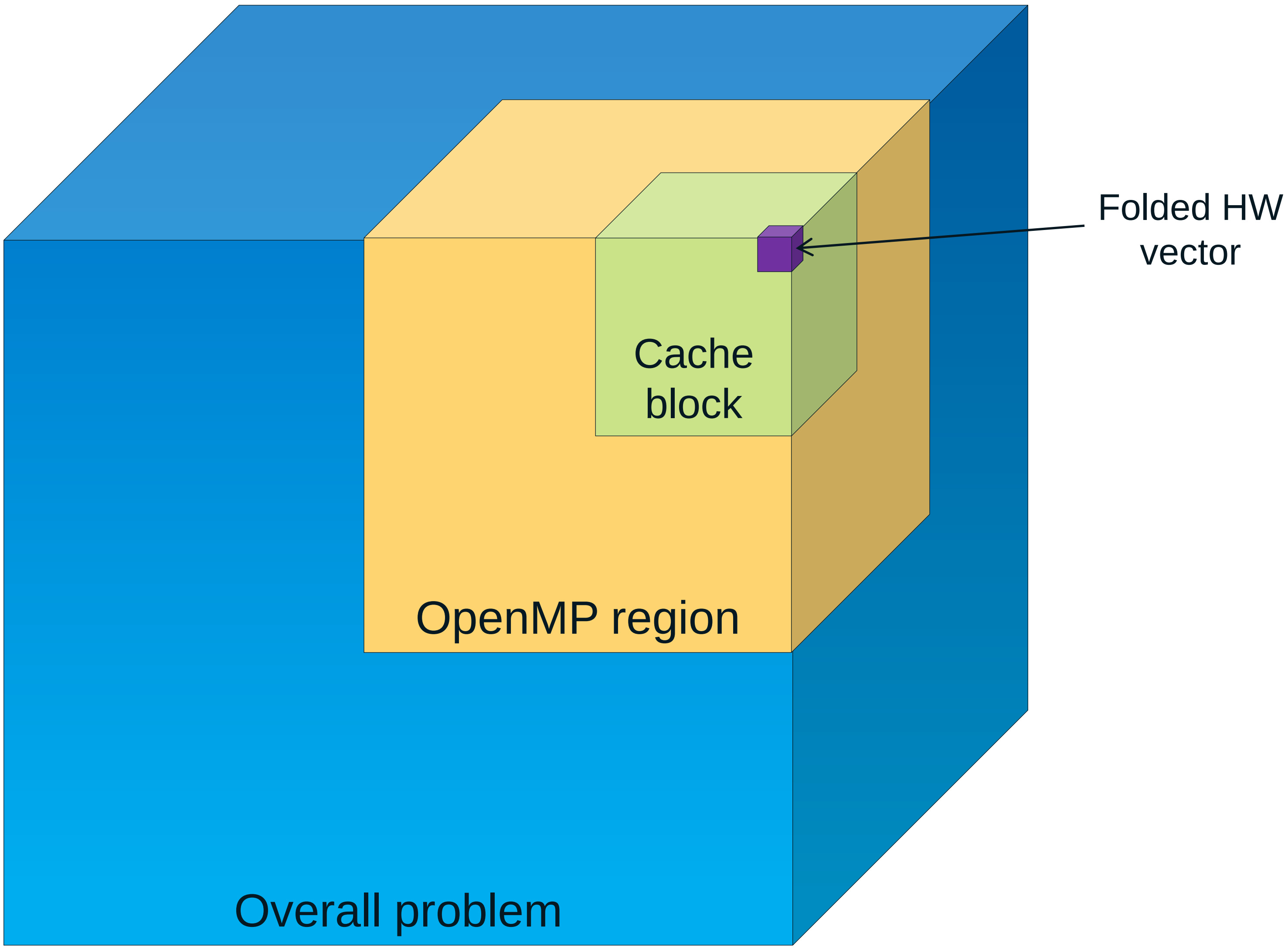
- The above class was generated from the code on the previous slide using this command: `./foldBuilder -st iso3dfd -or 16 -fold x=1,y=4,z=4 -p512`
  - See the foldBuilder help message for information on the options
- The above code is a small sample from over 900 lines of generated code
  - The resulting compiled 'calc_vector' method contains 125 instrs, including 7 SIMD FMAs, 48 SIMD add/sub/muls, 12 VALIGND, and 12 VPERMI2D
  - It also contains scalar reference and prefetch methods

Loop-code generator

Script that generates code for nested loops

- Input: Very simple DSL (domain-specific language)
  - omp loop(y) { crew loop(x) { loop(z) { calc(stencil); } } }
  - Can easily change loop types, index ordering
- Output: C++ code to be included in function bodies
  - Loops annotated with OMP/CREW as requested
  - Inner loop might generate several loops:
    - Prefetch L2
    - Prefetch L1
    - Calculate stencil and prefetch L2 and L1
    - Calculate and prefetch L1 only to avoid over-prefetching L2

Loops applied at multiple block levels



Memory accessor

- C++ classes to allocate and access 4D matrices of vectors of floats or doubles
  - Construction specifies ‘n, x, y, z’ dimensions and padding sizes; padding includes halos
  - Read and write access via methods: per vector for speed; per element for debug, validation, etc.
- Actual memory layout is encapsulated and defined via inheritance
  - Map 4-D (n, x, y, z) to 1-D mem address
    - 24 simple permutations of minor-to-major ordering
    - More complex mappings possible, e.g., tiling, space-filling curves
  - ‘n’ dimension is used for time and/or grid indices
- Uses concrete inheritance to allow inlining
  - Gives compiler full access to memory-layout formula
  - Allows common sub-expression elimination and other optimizations

Debug features

Can enable or disable various output by setting macros and rebuilding, e.g.,

- TRACE: print each stencil calculation
- TRACE_MEM: print each matrix read, write, prefetch, eviction
- TRACE_INTRINSICS: print before-and-after each permutation

Built-in memory-access tracker

- Models an infinite L1 or L2 cache
- Tracks reads, writes, prefetches, evictions
- Reports any un-prefetched read or un-read prefetch
- Reports summary stats
- Very useful for debugging prefetch code

Example cache-model output

```
modeling cache...
cache L2: redundant prefetch of 0x2aaabfa45a40 at line 193 after a read at line 85.
cache L2: redundant prefetch of 0x2aaabfa45a80 at line 193 after a read at line 85.
cache L2: redundant prefetch of 0x2aaabfa45a40 at line 195 after a prefetch at line 193.
cache L2: redundant prefetch of 0x2aaabfa45a40 at line 196 after a prefetch at line 195.
…
done modeling cache...
cache L2: read of 0x2aaabf9c3240 from line 85 without any eviction.
cache L2: read of 0x2aaabf9c3280 from line 85 without any eviction.
…
cache L2: prefetch of 0x2aaabfa53b00 from line 318 without any read.
cache L2: prefetch of 0x2aaabfa53b40 from line 318 without any read.
…
cache L2 stats:
 cur size = 324714 lines (19.8190 MB).
 max size = 324714 lines (19.8190 MB).
 ave size = 185126 lines (11.2992 MB).
 num reads = 722400.
  num reads of missing lines = 0.
  num lines read but never evicted = 321700.
 num prefetches = 1458800.
  num prefetches of lines never subsequently read = 3014.
  num prefetches of lines already in cache = 404686.
 num evictitions = 0.
  num evictions to non-existant lines = 0.
 num prefetches into L1 = 729400.
  num prefetches into L1 of missing lines = 0.
```

Using YASK

Initial build and test

Install

- Download the code from the 'GIT REPO' link at https://01.org/yask
- Install all the prerequisites from the README file

Build and run the default test program

- Type 'make -arch *arch-code*' per the README file
- Run the program using the stencil-run.sh script
  - Use the -mic option to run on a Xeon Phi coprocessor
  - Run under SDE to emulate hardware you don't have
  - Run natively
- If it doesn't build and/or run, check the prerequisites

Typical run and output

Settings are printed

- Sizes: problem, region, block, cluster and vector
- Stencil shape and order
- Other miscellaneous compile-time and run-time settings

A number of trials (default=3) are run

- Each trial executes a number of iterations (default=50)
- Time and throughput (million points per sec) are printed
- Best result across the trials is re-printed

Validation

- If the '-v *n*' option was used, *n* validation iteration(s) are run, and 'PASSED' or 'FAILED' is printed
- Validation is slow; run with a small problem size

Use model

Review

- YASK is a tool for exploring the stencil design space
- It is not a library

Typical usage model

- Identify stencil(s) used in your application
- Use existing stencil(s) in YASK or write your own
- Use YASK to find well-performing parameters
- Integrate the stencil code back into your application

Run-time options

Settings controlled from the ‘stencil.*arch*.exe’ binary

- Problem size: -d
- Number of regions: -nregions
- Cache-block size: -b
- Padding: -p
  - Used to fine-tune data alignment across rows and columns
  - The specified value is added to the halo size
- Number of trials and iterations: -t, -i, -v
- Run with ‘-h’ option to get help

Settings controlled from the ‘stencil-run.sh’ script

- Binary selection via ‘arch’ option
- OpenMP affinity
- Which Xeon Phi coprocessor or other host to use
- Number of CPU cores and threads
- Run with ‘-h’ option to get help

Stencil customization

Stencil Type

- Use the ‘stencil=*stencil-name*’ argument to the make command to select a stencil
  - The *stencil-name* string is passed to the foldBuilder tool
- Current provided stencils
  - ‘iso3dfd’: an isotropic acoustic wave equation
  - ‘3axis’, ‘9axis’, ‘3plane’, and ‘cube’: common 3D symmetric shapes (defined in the vector-folding paper)
  - ‘ave’: the simple 27-pt stencil from the miniGhost benchmark
  - ‘awp’: a simplified version of AWP-ODC earthquake simulation stencils
- Write your own by modifying code in src/foldBuilder
  - Implement the StencilBase interface using the stencils/*Stencil.hpp files as examples
  - Modify main.cpp to add appropriate command-line options and instantiate your new stencil class

Stencil customization (cont.)

Stencil size

- Use the ‘order=*n*’ argument to the make command
  - The *n* value is passed to the ‘foldBuilder’ tool
  - Default=16; 2 for ‘ave’ stencil; not used for ‘awp’
  - For the current example stencils, any even value of *n* is allowed, except for ‘awp’
  - Also controls size of halos automatically allocated by kernel
- Write your own by modifying code in src/foldBuilder
  - Follow the existing examples to pass the ‘order’ parameter to your stencil code if applicable

Other parameters

- If you’re developing your own stencil, you can add more parameters similar to the ‘order’ one

Stencil customization (cont.)

Advanced

- The provided stencils assume uniformity across the entire 3D grid
  - The ‘foldBuilder’ tool evaluates the stencil code only from the origin to the extent of a vector
- Some stencil applications require special code at boundaries or other conditions
  - To achieve this using the ‘foldBuilder’ tool, you can provide a parameter to distinguish each condition, e.g., top boundary, bottom boundary, etc.
  - Then, you would need to generate separate code for each condition
  - For even more complex stencils, you may need to study and modify the ‘foldBuilder’ code beyond adding new stencils and command-line parameters

Vector-folding customization

Vector fold

- Use the fold='x=*n*,y=*n*,z=*n*' argument to the make command to control how much vectorization is done in each dimension
  - The values are passed to the 'foldBuilder' tool
  - Example: make fold='x=1,y=2,z=8' generate code using a 1x2x8 fold
- See the vector-folding paper for a detailed discussion

Vector cluster

- Use the cluster='x=*n*,y=*n*,z=*n*' argument to the make command to control how many vectors are calculated and output in each 'calc' method
  - The values are passed to the 'foldBuilder' tool
  - The default is 1x1x1, or one HW vector

Loop-structure customization

The ‘gen-loops.pl’ script creates the loop-control code

- There are 3 loop-control codes
  - ‘Outer’ loops break the whole problem into OpenMP regions (typically, only one OpenMP region is used)
  - ‘Region’ loops break each OpenMP region into cache blocks
  - ‘Block’ loops iterate over each vector cluster in a cache block

Usage

- See the Makefile for default invocations or run ‘make -n’
- Run ‘./gen-loops.pl’ without any parameters to get help on more options: index ordering, OpenMP scheduling, etc.
- Run the script before the make command or specify the *LOOP_ARGS variables in the make command to override

Misc. advanced customization

More compile-time options to the make command

- Use ‘crew=*n*’ to enable (n=1) or disable (n=0) Intel Crew threading
  – If you get a link-time error that ‘kmp*’ symbols cannot be found, your compiler does not support crew; use ‘crew=0’
- Use ‘real_bytes=*n*’ to set the size of a float: n=4 for single-precision or n=8 for double-precision (default=4; 8 for ‘ave’ stencil)
- Use ‘MACROS='*macro-settings*'’ set CPP macros
  – ‘MAP_4D=*class-name*’ to change the memory layout of 4D grids (default=Map1432; similar macro for 3D grids)
  – ‘PFDL1=*n1* PFDL2=*n2*’ to change the prefetch distances (defaults=1,8); only used in the prefetch code generated from ‘gen-loops.pl’, not in compiler-generated prefetch code
  – Example: ‘make MACROS='PFDL1=2 PFDL2=15'’
  – See stencil.hpp for most macro definitions

Collaboration

Use the blog at https://01.org/yask to ask and/or answer questions

Submit useful changes for review via github

Contact the author of this presentation for further collaboration opportunities