



Y.A.S.K.

Yet Another Stencil Kernel

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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: hierarchy sizes, wave-front blocking, MPI
- Stencil, vectorization, loop, and advanced customization
- Collaboration

Overview

YASK: Yet Another Stencil Kernel

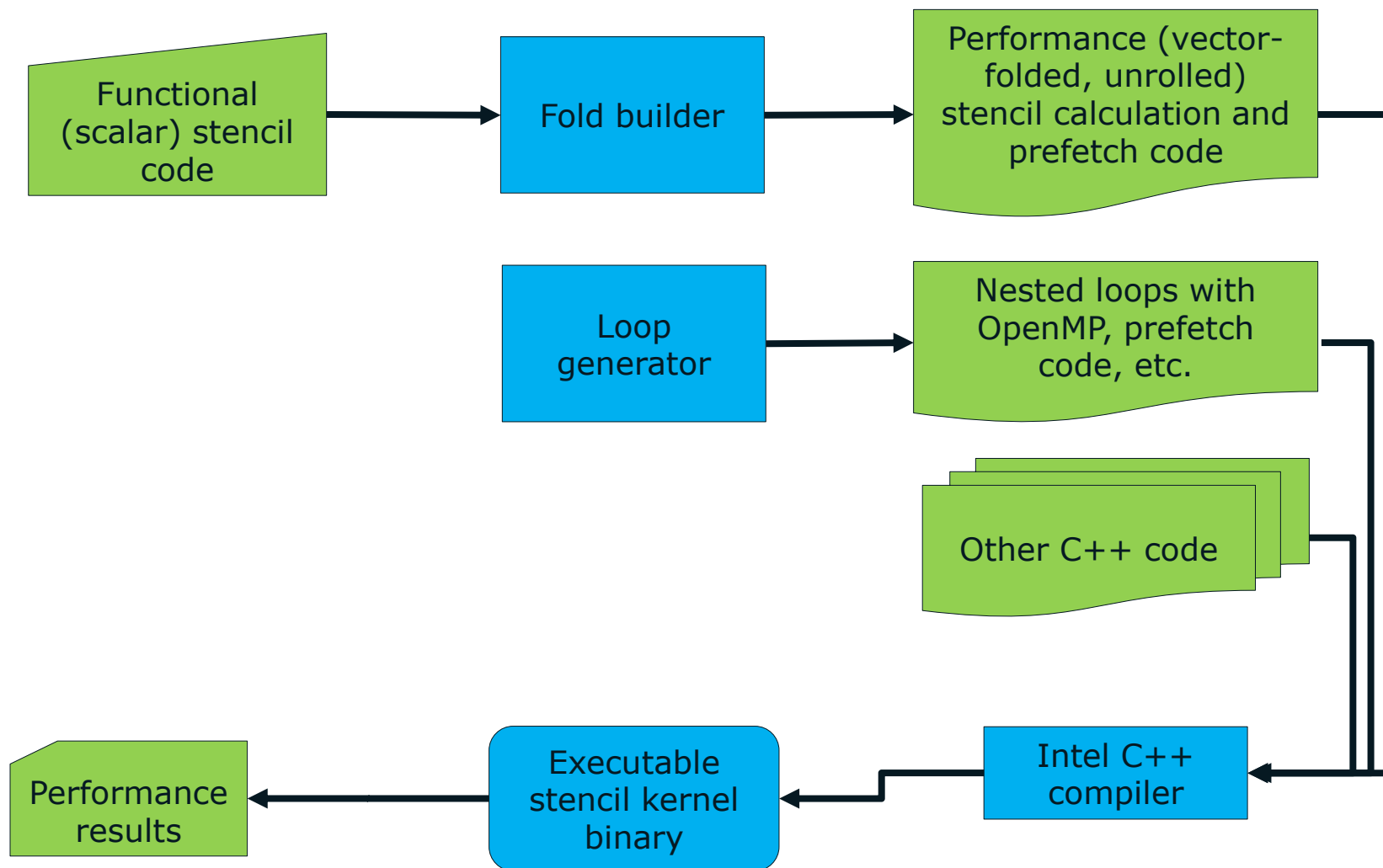
- Goal: facilitate exploration of the stencil-performance design space for Intel® Xeon Phi™ coprocessor or any Intel® Xeon™ processor supporting the AVX, AVX2, or AVX-512 instruction sets

Features

- Supports trade-off studies for coding options for
 - Vector-folding
 - Cache blocking
 - Memory layout
 - Loop construction
 - Temporal wave-front blocking
 - And more
- Is a collection of C++ code, code-generators and other scripts
- Focused on single-node OpenMP optimizations
 - Minimal MPI enabled at this time

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

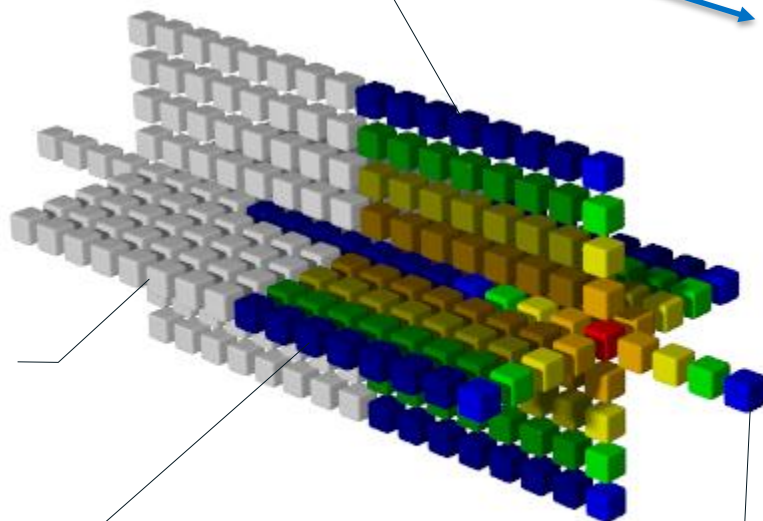
- Refer to paper on [Vector Folding from HPCC 2015](#)

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)



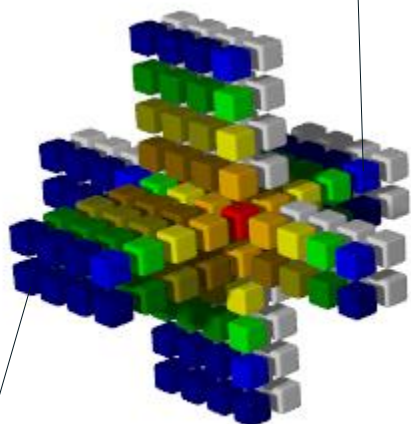
One 8-element
vector output per
iteration

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*



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)



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



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

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

```
class Iso3dfdStencil : public StencilOrderBase {
...
  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;
  }
}
```

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

Write function to
define equation for
"pressure" update

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

Example output stencil code

```
class struct StencilContext_iso3dfd:public StencilContext {
...
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);
}
...
}
```

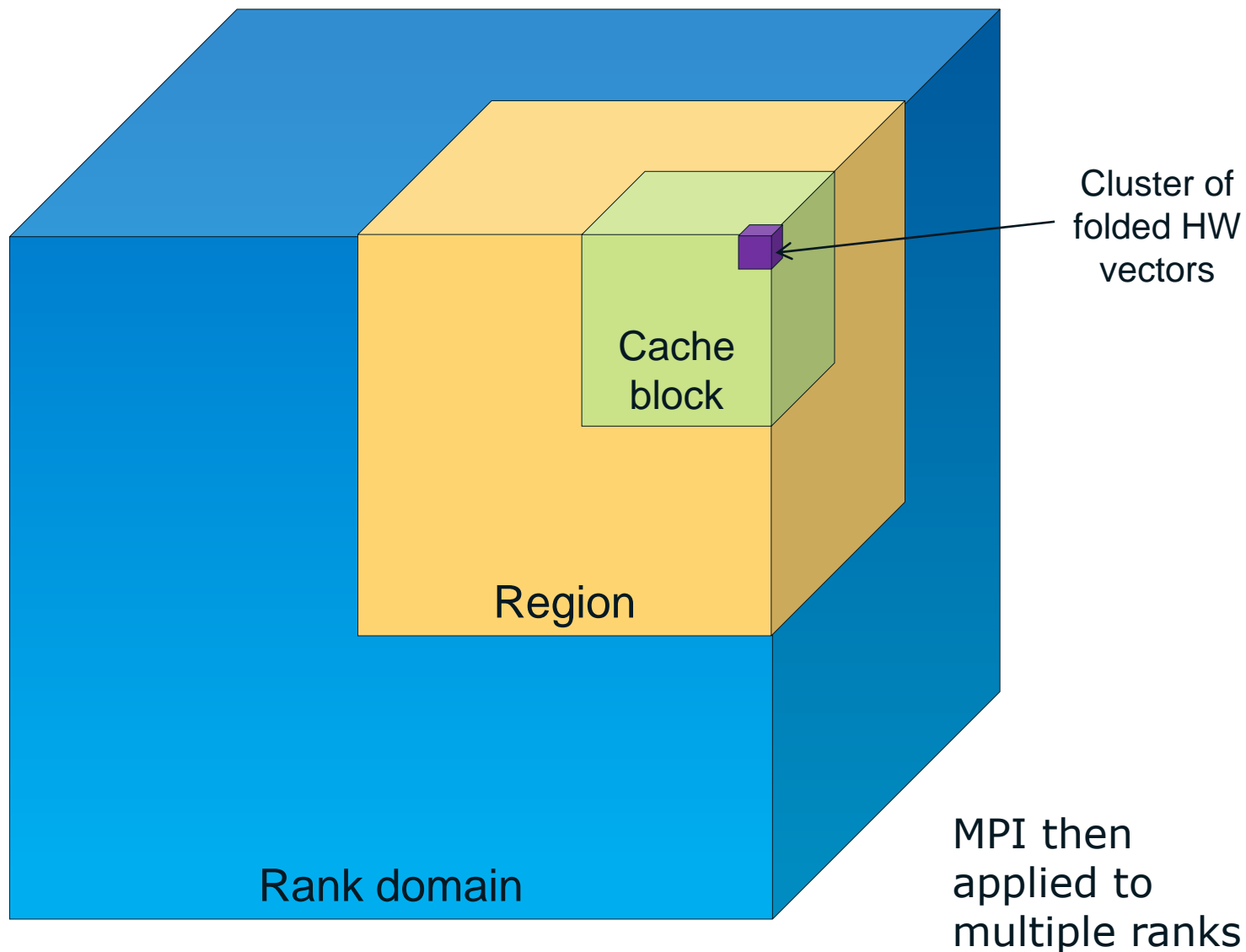
- The above class was generated from the code on the previous slide using this command: `./foldBuilder -st iso3dfd -or 16 -fold x=4,y=4,z=1 -p512`
 - See the foldBuilder help message for information on the options
- The above code is a small sample from over 2500 lines of generated code
 - The 'calc_vector' method, when inlined into an inner loop, compiles to ~110 instrs, including 5 SIMD FMAs, 47 SIMD add/sub/muls, 12 VALIGND, and 12 VPERMI2D instrs
 - It also contains methods for scalar reference and prefetch

Loop-code generator

Script that generates code for nested loops

- Input: Very simple DSL (domain-specific language)
 - `omp loop(y) { loop(x, z) { calc(stencil); } }`
 - Can easily change loop types, index ordering
- Output: C++ code to be included in function bodies
 - Loops annotated with OMP as requested
 - Inner loop might generate several loops, e.g.,
 - 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 3D & 4D matrices of vectors of floats or doubles
 - Construction specifies 'n, x, y, z' dimensions and padding sizes; padding includes halos (add 'n' for 4D)
 - Read and write access via methods: per vector for highest speed; per element for scalar code.
- Actual memory layout is encapsulated and defined via inheritance
 - Map 3D or 4D indices 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 evictions = 0.
    num evictions to non-existent 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 *name* -stencil *name*' per the README file
- Run the program using the stencil-run.sh script
 - Run natively on Xeon™ or Xeon Phi™ processors
 - Use the -mic option to run on a Xeon Phi™ coprocessor
 - Run under SDE to emulate hardware you don't have
- If it doesn't build and/or run, check the prerequisites

Typical run and output

Settings are printed

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

A number of trials (default=3) is run

- Time and throughput (points per sec) are printed
- FP-rate is estimated based on number of FP ops in original scalar spec
- Best result across the trials is re-printed

Validation

- If the '-v' option was used, a non-vectorized, non-tiled version of the code is run, the results are compared, 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

Common run-time options

Settings controlled from the `'stencil-run.sh'` script

- Binary selection via `'arch'` option
- OpenMP affinity
- Which Xeon Phi coprocessor or other host to use
- Run with `'-h'` option to get help

Settings controlled from the `'stencil.arch.exe'` binary (passed through from the `stencil-run.sh` script)

- Spatial/temporal rank-domain size (overall problem if not using MPI): `-d*/-dt`
- Spatial/temporal region size (used for temporal wave-front blocking): `-r*/-rt`
- 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: `-t`
- Validation: `-v`
- Run with `'-h'` option to get help

Enabling temporal wave-front blocking

Purpose

- The temporal blocking in YASK is designed to exploit large shared caches, e.g., when using the Intel® Xeon Phi™ processor in MCDRAM cache mode

Usage

- Temporal wave-front blocking is done using the “regions” level of the hierarchy shown earlier
 - Spatial blocks within each region are evaluated in parallel using OpenMP
 - The time slices within each region are evaluated sequentially to reuse memory
 - Regions are evaluated sequentially to increase shared-cache locality
- Executable run-time options
 - `-rt <n>` sets the number of time slices in each region
 - `-r* <n>` sets the spatial size of each region
 - Example: `stencil-run.sh -d 1920 -dt 50 -r 768 -rt 25`
 - Note: the default setting of `-rt` is one (1), and the default setting of `-r` is zero (0), which means the region size is the same as the rank size.

Enabling MPI

Purpose

- The current MPI implementation in YASK is minimal: it is only applied in the x-dimension
- It was targeted for one multi-socket node or a very small number of nodes, not large clusters

Usage

- Compile with MPI enabled using “make mpi=1 ...”
- Run “stencil-run.sh -ranks <n>” to control the number of ranks used
- Note: the -d* options control the rank size (weak scaling), so divide the x-size by the number of ranks to keep the problem size constant (strong scaling)

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 include your new `.hpp` file

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; ignored for `'awp'`
 - For the current example stencils, any even value of n is allowed
 - 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
 - Another (often simpler) way to handle boundary code is to write it in scalar code that is run after the generated vector code; this would be added to your final application, but not necessarily in the YASK kernel

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'` generates code using a 1x2x8 fold
 - Make sure the product of the fold lengths equals the vector size of the target architecture and FP precision (single or double)
- 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
 - This essentially implements loop unrolling in multiple dimensions

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 `'EXTRA_MACROS='macro-settings'` set other CPP macros
 - `'PFDL1=n1 PFDL2=n2'` to change the prefetch distances; only used in the prefetch code generated from `'gen-loops.pl'`, not in compiler-generated prefetch code
 - Example: `'make MACROS='PFDL2=15''`
 - See `*.hpp` for macro definitions
- Run `'make settings'` to see other make variables

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

