Generalizing a DSL for Structured Dependency ("Stencil-like") Codes to OpenMP* Loops

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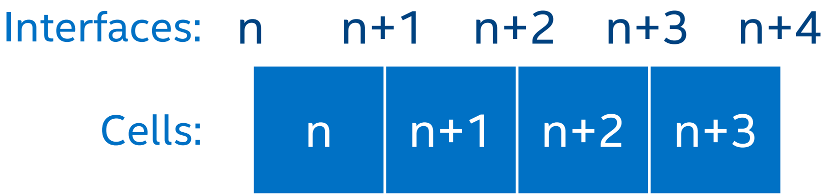
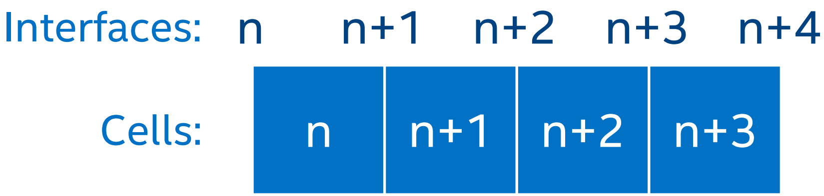
A Simple Example (1/3)



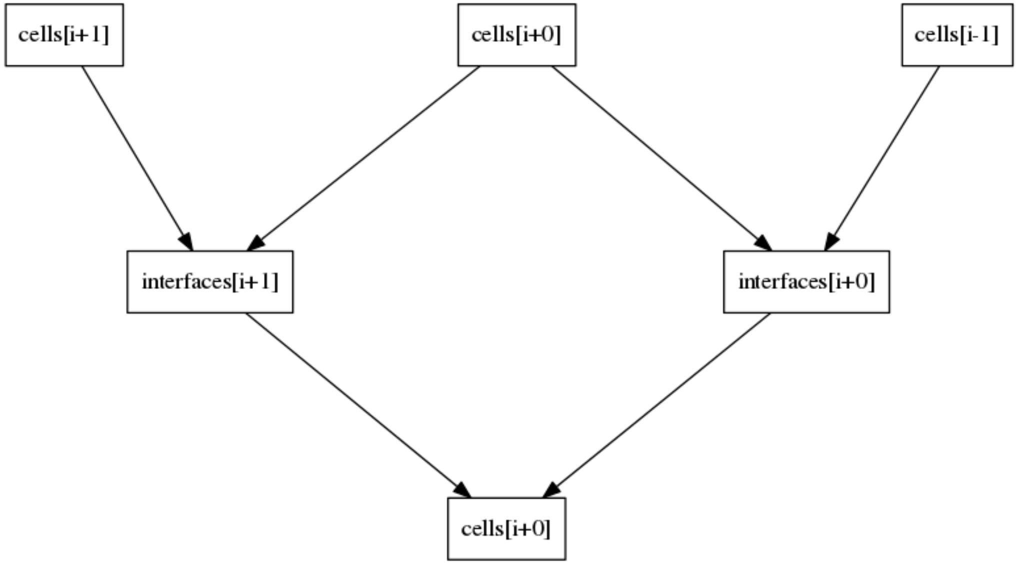

```
// Two simple kernels
void flux(double prev_cell, double next_cell, double &interface);
void integrate(double prev_interface, double next_interface, double &cell);

// Typical parallel implementation (in 1D)
#pragma omp parallel for simd
for (uint32_t itf = first_itf; itf < last_itf; ++itf)
{
     flux(cells[itf-1], cells[itf], interfaces[itf]);
}
#pragma omp parallel for simd
for (uint32_t c = first_cell; c < last_cell; ++c)
{
     integrate(interfaces[c], interfaces[c+1], cells[c]);
}
```

A Simple Example (2/3)



Data-flow DAG:

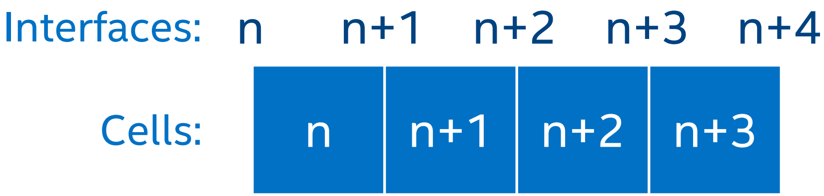


3 cell values as input

2 interface values as intermediates

1 cell value as output

A Simple Example (3/3)




```
// Two simple kernels
void flux(double prev_cell, double next_cell, double &interface);
void integrate(double prev_interface, double next_interface, double &cell);

// Rolling update implementation (in 1D)
#pragma omp parallel for
for each tile (first_cell, last_cell)
{
     double tmp_itf[2];
     flux(cells[first_cell-1], cells[first_cell], tmp_itf[0]); // Prologue
     for (uint32_t c = first_cell; c < last_cell; ++c)          // Steady-state
     {
          flux(cells[c], cells[c+1], tmp_itf[1]);
          integrate(tmp_itf[0], tmp_itf[1], cells[c]);
          tmp_itf[0] = tmp_itf[1];
     }
}
```

This forward dependency prevents auto-vectorization.

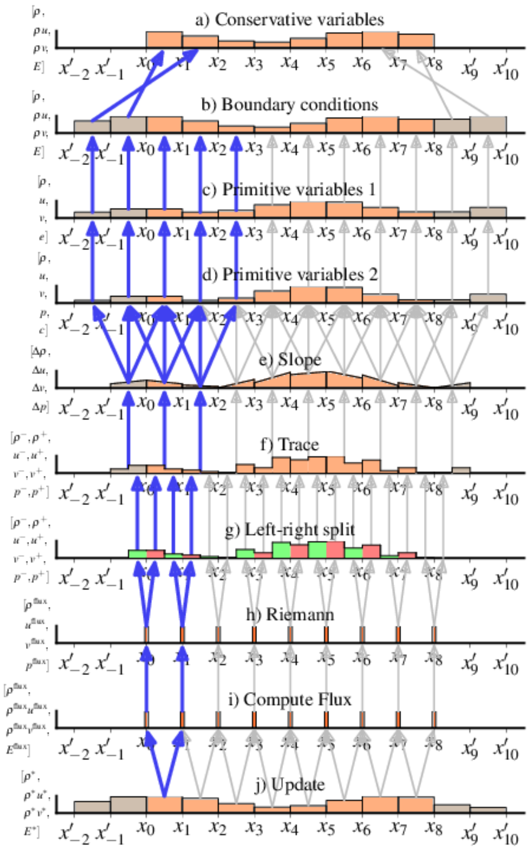
A Complicated Example – CEA's Hydro2D

- Implements 9 "parallel kernels" as:

```
for all cells in a slab:
  function();
synchronize



make_boundary();
constoprim();
equation_of_state();
slope();
trace();
qleftright();
riemann();
cmpflx();
updateConservativeVars();
```



Why a DSL/Code Generator?

Data dependency analysis is error-prone and time-consuming.

- Needs to be repeated each time application functionality is changed.
- Application functionality may change many times during optimization studies.
- Dependency analysis for proxy applications won't match the legacy application.

Rolling update code follows a pattern => copy-paste errors.

- Very easy to get a temporary index, or the rolling buffer size, wrong.

Rolling update loops have very real data dependencies.

- Compiler cannot vectorize the code (at all).
- Explicit vectorization requires intrinsics, SIMD classes or ugly OpenMP code.

Input Parameters

- Kernel description(s):

```
integrate:
        declaration: integrate(flux_t lf, flux_t rf, cell_t &ic);
        inputs: |
            lf : flux(q?[j?][i?])
            rf : flux(q?[j?][i?+1])
        outputs: |
            ic : integrated(q?[j?][i?])
```

Kernels are elemental functions representing production rules. "?" can be substituted.

- Axiom(s):

```
double cell[j?][i?]
```

Axioms exist before any kernels. Infinite extent assumed.

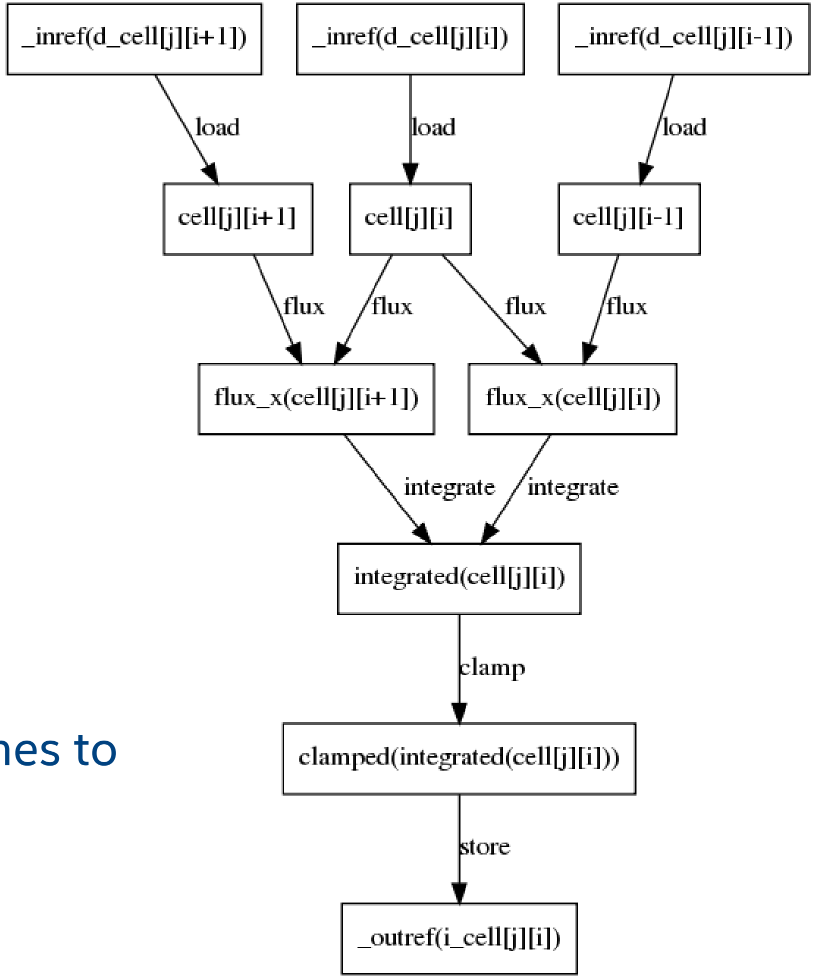
- Goal(s):

```
integrated(cell[j][i]) => double cell[j][i]
```

Inference works backward from goals to compute specified index.

Stage 1: Inference

- Start at a goal (e.g. i_cell[j][i]).
- Repeatedly apply rules and substitutions until we reach:
  - An axiom (e.g. d_cell[j][i]); or
  - A node already in the DAG.
- We have prefixed function names to ensure unique variable names.



Stage 2: Loop Nest Optimizations

- Serves two purposes:
  1. Identifies functions with a spatial relationship and fuses them; and
  2. Aggressively fuses loop nests (where safe to do so).

- In many cases, it is safe to fuse all loops – only “concavity” prevents it:

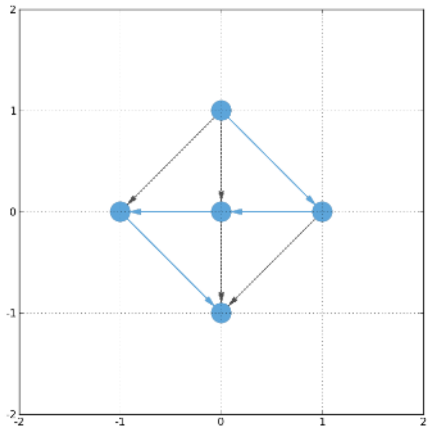
```
#pragma omp parallel for simd reduction(+:sum)
for (uint32_t i = 0; i < N; ++i)
{
    sum += f(input[i]);
}
#pragma omp parallel for simd
for (uint32_t i = 0; i < N; ++i)
{
    output[i] = g(sum);
}
```

Using the reduced value requires all iterations of the first loop to be executed.

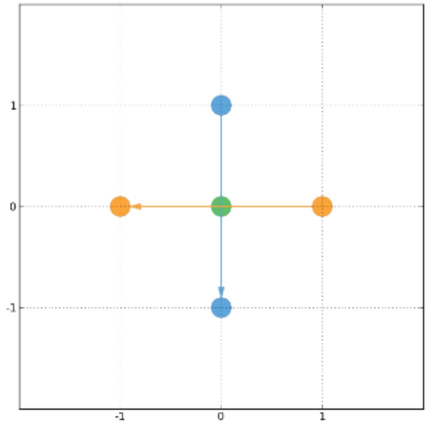
Stage 3: Rolling Analysis

- All spatial references to a variable can be visualized as (another) “reuse” DAG.
  - Vertices = Spatial references
  - Edges = Child node is “reachable” from parent node, using given loop order and stride

- Vertices with input degree of zero are the first time that point in the iteration space has been visited for this variable; others can be loaded from intermediate storage.



2D Laplace, Stride 1



2D Laplace, Stride 2

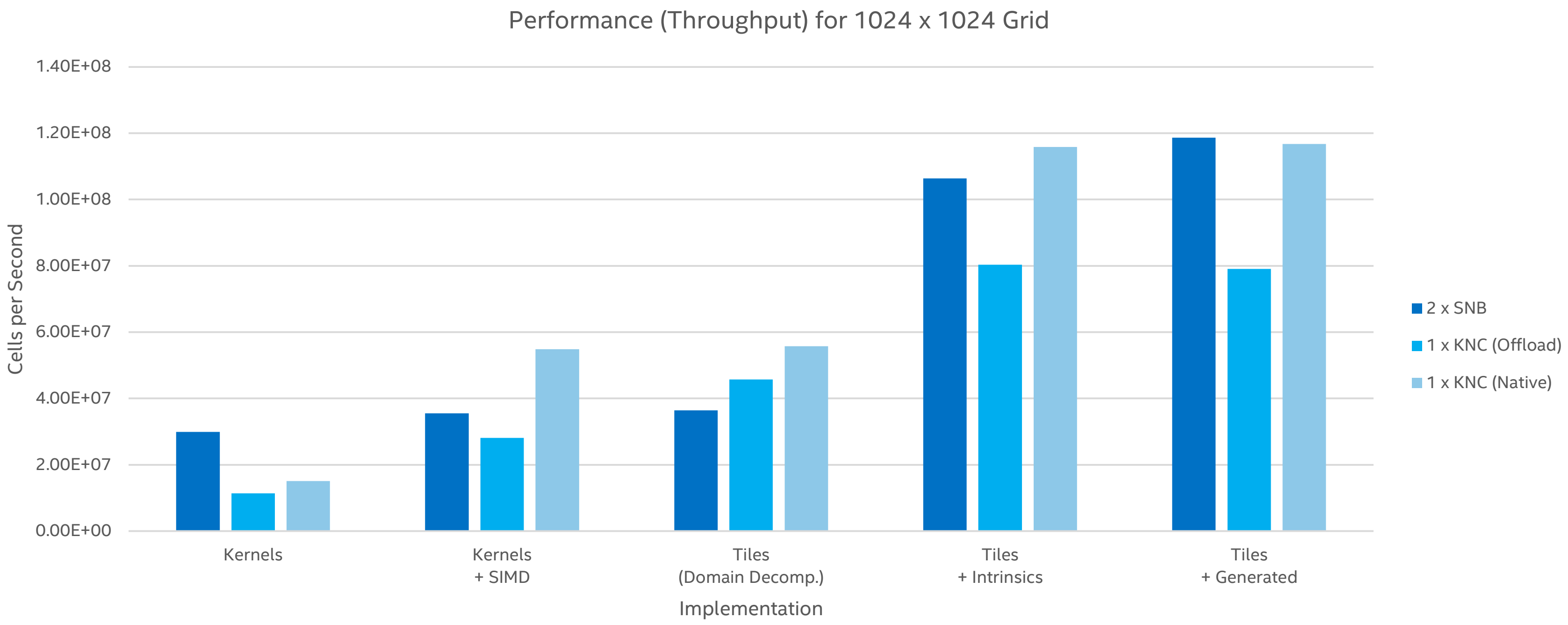
Stage 4: Code Generation

- For each loop nest:
  - Open loop nest.
  - Generate code for children (other loop nests and/or kernel calls).
  - Close loop nest.

- For each variable:
  - Map from global to temporary (e.g. flux[j][i] => tmp_flux[i-istart])

- For vectorization:
  - "#pragma omp simd" if loop has no dependencies; otherwise
  - Strip-mine (and interchange, if necessary) with intrinsic function to rotate buffers

Case Study: CEA's Hydro2D



Generalizing to OpenMP*

- Why are we interested in language extensions?
  - Our YAML framework is ugly and not user-friendly.
  - User code already contains information that must be re-specified in our framework (*e.g.* loop bounds, boundary conditions, program order, variable names)
  - Adoption rate of language extensions appears much higher than that of frameworks (*e.g.* OpenMP SIMD extensions vs Threading Building Blocks)

- We propose to extend OpenMP 4.5 task syntax to specify dependencies between iterations of different loops.

Proposed Language Extensions – Draft

```
#pragma omp pipeline \
depend(inout:cell) intermediate(flux_x) \
iterators(j:j_itf,j_cell,i:i_itf,i_cell)
{

  #pragma omp pipeline block \
   depend(inout:cell:*,*)
  initialize_boundary_conditions(cell);

  #pragma omp pipeline loop simd collapse(2) \
   depend(in:cell:j,i-1) depend(in:cell:j,i) depend(out:flux_x:j,i)
  for (int j_itf = jstart; j_itf < jend; ++j_itf)
  {
    for (int i_itf = istart; i_itf < iend+1; ++i_itf)
    {
      flux(cell[j_itf][i_itf-1], cell[j_itf][i_itf], flux_x[j_itf][i_itf]);
    }
  }

  #pragma omp pipeline loop simd collapse(2) reduction(max:maxCell[j]) \
   depend(in:flux_x:j,i) depend(in:flux_x:j,i+1) depend(out:cell:j,i)
  for (int j_cell = jstart; j_itf < jend; ++j_itf)
  {
    for (int i_cell = istart; i_itf < iend; ++i_itf)
    {
      integrate(flux_x[j_cell][i_cell], flux_x[j_cell][i_cell+1],
                cell[j_cell][i_cell]);
      maxCell[j_cell] = max(maxCell[j_cell], cell[j_cell][i_cell]);
    }
  }
}
```

pipeline
A region containing one or more pipeline stages.

pipeline loop/block
Marks a loop or structured block as a pipeline stage.

intermediate(*list*)
Declares one or more storage locations used only to pass data between pipeline stages.

depend*(dependence-type : list : vec)*
Enforce constraints on the scheduling of loop iterations in different stages of the same pipeline region.

New/extended keywords highlighted in red.

Summary

- Produced a prototype analysis + code generation tool for “rolling updates”.
- Impressive performance results for real-life benchmark.
- Future work:
  - Optimization heuristics (e.g. kernel fusion, redundant compute, halo size)
  - Compiler/language integration

- If your code matches the following criteria, please e-mail us (or talk to me):
  - Multiple parallel/vector loops over a single domain.
  - Local, known (i.e. structured) dependencies between domain elements.

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