ExaSlang: A Domain-Specific Language for Highly Scalable Multigrid Solvers

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Motivation

void Smoother() {
    for (int fragmentIdx = 0; fragmentIdx < 1; fragmentIdx++) {
        if (isValidForSubdomain) {
            if (neighbor_isValid && neighbor_isRemote) {
                for (int y = iterationOffsetBegin; (y < iterationOffsetEnd); ++y) {
                    for (int x = iterationOffsetBegin; (x < iterationOffsetEnd); ++x) {
                        // code for parallel for loop
                    }
                }
            }
        }
    }
}

#pragma omp parallel for schedule(static) num_threads(27)
for (int w = 0; (w<1) ; w += 1) { for (int z = 1; ( z <98) ; z += 1) { for (int y = 1; ( y <98) ; y += 1) { for (int x = 100; ( x <101) ; x += 1) {
    // code for parallel for loop
}
} } }

#pragma omp parallel for schedule(static) num_threads(27)
for (int w = 0; (w<1) ; w += 1) { for (int z = 1; ( z <98) ; z += 1) { for (int y = 97; ( y <98) ; y += 1) { for (int x = 4; ( x <5) ; x += 1) {
    // code for parallel for loop
}
} } } }
Motivation

```c
void Smoother() {
    for (int fragmentId = 0; fragmentId < fragmentIds.size(); ++fragmentId) {
        if (isValidForSubdomain) {
            if (neighbor_isValid[2] && neighbor_isRemote[2]) {
                // OpenMP parallel for schedule(static) num_threads(27)
                for (int fragmentIdx = 0; fragmentIdx < 1; ++fragmentIdx) {
                    if (isValidForSubdomain) {
                        for (int w = 0; (w < 1); ++w) {
                            for (int z = 1; (z < 98); ++z) {
                                for (int y = 97; (y < 98); ++y) {
                                    for (int x = 100; (x < 101); ++x) {
                                        buffer_Send_0[1][(w*9409 + x) + (y*97 + z)] = slottedFieldData_Solution[solutionId][1][(w*919304 + x) + (y*104 + z) + (z*97) + 102406];
                                    }
                                }
                            }
                        }
                    }
                }
            }
        }
    }
}

#pragma omp critical
reqOutstanding_Send_0[1] = false;

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void Smoother() {
    for (int fragmentId = 0; fragmentId < fragmentIds.size(); ++fragmentId) {
        if (isValidForSubdomain) {
            if (neighbor_isValid[2] && neighbor_isRemote[2]) {
                // OpenMP parallel for schedule(static) num_threads(27)
                for (int fragmentIdx = 0; fragmentIdx < 1; ++fragmentIdx) {
                    if (isValidForSubdomain) {
                        for (int w = 0; (w < 1); ++w) {
                            for (int z = 1; (z < 98); ++z) {
                                for (int y = 97; (y < 98); ++y) {
                                    for (int x = 100; (x < 101); ++x) {
                                        buffer_Send_0[1][(w*9409 + x) + (y*97 + z)] = slottedFieldData_Solution[solutionId][1][(w*919304 + x) + (y*104 + z) + (z*97) + 102406];
                                    }
                                }
                            }
                        }
                    }
                }
            }
        }
    }
}
```

SIMD extensions

OpenMP
Motivation

Why not concentrate on the algorithmic description?

```plaintext
Function Smoother() : Unit {
    communicate Solution
    loop over Solution {
        Solution = Solution + 0.8 * (1.0 / diag(Laplace)) * 
                   (RHS - Laplace * Solution)
    }
}  
```
Motivation

Why not concentrate on the algorithmic description?

Function Smoother () : Unit {
    communicate Solution
    loop over Solution {
        Solution = Solution + 0.8 * (1.0 / diag(Laplace)) * (RHS - Laplace * Solution)
    }
}

- Productivity
  - Algorithm description at high-level
  - Hide low-level details from programmer

- Portability
  - Support different target platforms from the same description
  - Support different target languages from the same description

- Performance
  - Portable: high performance on different target platforms
  - Competitive: comparable performance to hand-written code
ExaSlang
**ExaSlang**

- **ExaStencils language**
- Abstract description for generation of massively parallel geometric multigrid solvers
- Multi-layered structure → set of Domain-Specific Languages (DSLs)
- Top-down approach: From abstract to concrete
- Very few mandatory specifications at one layer → room for decisions at lower layers based on domain knowledge
- External Domain-Specific Language
  - Better reflection of extensive ExaStencils approach
  - Enables greater flexibility of different layers
  - Eases tailoring of DSL layers to users
  - Enables code generation for large variety of target platforms
Basic Multigrid Ideas

Residual on fine grid

Residual on coarse grid

Smoother applied
Basic Multigrid Ideas

Multigrid method

1. Pre-smoothing
2. Calculation of residual
3. Restriction
4. Recursive call(s) or solve (at coarsest level)
5. Prolongation
6. Correction
7. Post-smoothing
ExaSlang: Multi-layered DSL Structure

Different layers of DSL tailored towards different users and knowledge.

1. Continuous Domain & Continuous Model
2. Discrete Domain & Discrete Model
3. Algorithmic Components & Parameters
4. Complete Program Specification
**ExaSlang: Multi-layered DSL Structure**

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4. Complete Program Specification
ExaSlang 4: Complete Program Specification

Properties

- Procedural
- Statically typed
- External DSL
- Syntax partly inspired by Scala
ExaSlang 4: Complete Program Specification

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• Statically typed
• External DSL
• Syntax partly inspired by Scala

Specification of

• Operations depending on the multigrid level
• Loops over computational domain
• Communication and data exchange
• Interface to 3rd-party code
Data Types

Simple and aggregate data types

- `Real`, `Integer`, `String`, `Boolean`
- `Complex<Real>`, `Complex<Integer>`

Algorithmic data types

Field

- Correspond to discretized (mathematical) variables
- Communication scheme via `Layout`
- Specify `Slot` number for multiple copies

Stencil

- Correspond to discretized (mathematical) operators
- (Nearly) arbitrary expressions possible
Computations

Loop over computational domain split into \textit{loop over fragments}

- Fragments stem from distribution across different cluster nodes
- Corresponds to global operation
- Optionally: reduction operators

\textbf{and} \textit{loop over \textless field\textgreater}

- Iteration over parts of fields possible
- Corresponds to local operation
- Optionally: Reduction operators

\begin{verbatim}
Function NormResidual @(coarsest and finest) () : Real {
    Variable res : Real = 0
    loop over fragments with reduction(+ : res) {
        loop over Residual @current with reduction(+ : res) {
            res += Residual @current * Residual @current
        }
    }
    return ( sqrt(res) )
}
\end{verbatim}
Level Specifications

Multigrid is inherently hierarchical and recursive

→ We need
  • Multigrid recursion exit condition
  • Access to other levels’ data & functions

→ Additionally, we want
  • Relative addressing
  • Aliases for certain levels
  • Variable definitions per level

Implementation

• Numerical values, e.g., @0 for bottom level
• Aliases, e.g., @all, @current, @coarser, @coarsest
• Simple expressions, e.g., @(coarsest + 1)
• Lists, e.g., @(1, 3, 5)
• Ranges, e.g., @(1 to 5)
Level Specifications: Example

Disjunct function definition

```
Function VCycle @((coarsest+1) to finest) () : Unit {
    repeat 3 times {
        Smoother @current ()
    }
    UpResidual @current ()
    Restriction @current ()
    SetSolution @coarser (0)
    VCycle @coarser ()
    Correction @current ()
    repeat 3 times {
        Smoother @current ()
    }
}
```

```
Function VCycle @coarsest () : Unit {
    /* ... solve directly ... */
}
```
Level Specifications: Example

Disjunct function definition

```plaintext
Function VCycle @((coarsest+1) to finest) () : Unit {
    repeat 3 times {
        Smoother @current ()
    }
    UpResidual @current ()
    Restriction @current ()
    SetSolution @coarser (0)
    VCycle @coarser ()
    Correction @current ()
    repeat 3 times {
        Smoother @current ()
    }
}

Function VCycle @coarsest () : Unit {
    /* ... solve directly ... */
}
```
Level Specifications: Example

No disjunction needed due to overloading

```haskell
Function VCycle @(coarsest to finest) () : Unit {
  repeat 3 times {
    Smoother @current ()
  }
  UpResidual @current ()
  Restriction @current ()
  SetSolution @coarser (0)
  VCycle @coarser ()
  Correction @current ()
  repeat 3 times {
    Smoother @current ()
  }
}

Function VCycle @coarsest () : Unit {
  /* ... solve directly ... */
}
```
Level Specifications: Example

Level Specification can be simplified further

```plaintext
Function VCycle @all () : Unit {
    repeat 3 times {
        Smoother @current ()
    }
    UpResidual @current ()
    Restriction @current ()
    SetSolution @coarser ()
    VCycle @coarser ()
    Correction @current ()
    repeat 3 times {
        Smoother @current ()
    }
}

Function VCycle @coarsest () : Unit {
    /* ... solve directly ... */
}
```
ExaStencils Transformation Framework
ExaStencils Framework

Abstract workflow:

Algorithmic description

parsing

Intermediate representation

prettyprinting

C++ output
ExaStencils Framework

Using a simple 1-step concept, we can do some refinements, e.g.,

```c
loop over Solution {
    // ....
}
```

is processed to

```c
for (int z = start_z; z < stop_z; z += 1) {
    for (int y = start_y; y < stop_y; y += 1) {
        for (int x = start_x; x < stop_x; x += 1) {
            // ....
        }
    }
}
```
ExaStencils Framework

Using a simple 1-step concept, we can do some refinements, e.g.,

```cpp
loop over Solution {
    // ....
}
```

is processed to

```cpp
for (int z = start_z; z < stop_z; z += 1) {
    for (int y = start_y; y < stop_y; y += 1) {
        for (int x = start_x; x < stop_x; x += 1) {
            // ....
        }
    }
}
```


→ Very cumbersome with 1-step approach. Need something more flexible!
ExaStencils Framework

Current workflow

1. DSL input (Layer 4) is parsed
2. Parsed input is checked for errors and transformed into the IR
3. Many smaller, specialized transformations are applied
4. C++ output is prettyprinted
ExaStencils Framework

Current workflow

1. DSL input (Layer 4) is parsed
2. Parsed input is checked for errors and transformed into the IR
3. Many smaller, specialized transformations are applied
4. C++ output is prettyprinted

Concepts

- Major program modifications take place only in IR
- IR can be printed to C++ code
- Small transformations can be enabled and arranged according to needs
- Central instance keeps track of generated program: StateManager
- Variant generation by duplicating program at different transformation stages
ExaStencils Framework

Transformations

- Transform program state into another one
- Are applied to program state in depth-first order
- May be applied to only a part of the program state
- Are grouped together in Strategies
ExaStencils Framework

Transformations

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Strategies

- Are applied in transactions
- Standard strategy that linearly executes all transformations is provided
- Custom strategies possible
ExaStencils Framework

Transactions

• Before execution, a snapshot of the program state is made
• May be committed or aborted

Checkpoints

• A copy of program state during compilation
• Restoration of program states
• Acceleration of variant generation for design space exploration
ExaStencils Framework

Example transformations:

```javascript
var s = DefaultStrategy("example strategy")

// rename a certain stencil
s += Transformation("rename stencil", {
    case x : Stencil if(x.identifier == "foo")
    =>
    {
        if(x.entries.length != 7) error("invalid stencil size")
        x.identifier = "bar"; x
    }
})

// evaluate additions
s += Transformation("eval adds", {
    case AdditionExpression(l : IntegerConstant, r : IntegerConstant)
    => IntegerConstant(l + r)
})

s.apply // execute transformations sequentially
```
ExaStencils Framework

Implemented workflow:

Algorithmic description

parsing

C++ output

prettyprinting
First Results
Program Sizes during Transformation

- V(3,3) cycle, Jacobi smoother, CG coarse grid solver
- Hybrid MPI/OpenMP

![Graph showing program sizes during transformation]
Generated Lines of Code

- **ExaSlang 4**
  - Jacobi: 244 lines, 11,259 lines of code
  - Gauss-Seidel: 236 lines, 9,600 lines of code
  - Red-Black GS: 240 lines, 9,776 lines of code

- **C++ Pure MPI**
  - Jacobi: 13,432 lines of code
  - Gauss-Seidel: 11,320 lines of code
  - Red-Black GS: 12,887 lines of code

- **C++ Hybrid MPI/OMP**
Weak-Scaling Results

Solution of Poisson’s equation in 3D, V(3,3) cycle, Jacobi, CG
Average time per V-cycle on JUQUEEN

![Graph showing weak-scaling results for solving Poisson's equation with Jacobi and CG methods using Pure MPI and various combinations of MPI and OMP parallelization.]
Summary

Presented

- Multi-layered DSL ExaSlang for multigrid-based numerical solvers
- Framework for specification of transformations and code generation
- Generation of highly scalable C++ code

Conclusions

- Code generation is a viable approach to generation of multigrid codes
- Specialized DSLs allow for concise algorithmic descriptions (Productivity)
- Generation of solvers for different target platforms (Portability)
- More work on optimizations needed, but scalability already good (Performance)
Thanks for listening. Questions?

ExaStencils – Advanced Stencil Code Engineering
http://www.exastencils.org

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