Polygeist: Affine C in MLIR

William S. Moses

wmoses@mit.edu

Lorenzo Chelini

l.chelini@tue.nl

Ruizhe Zhao

rz3515@ic.ac.uk

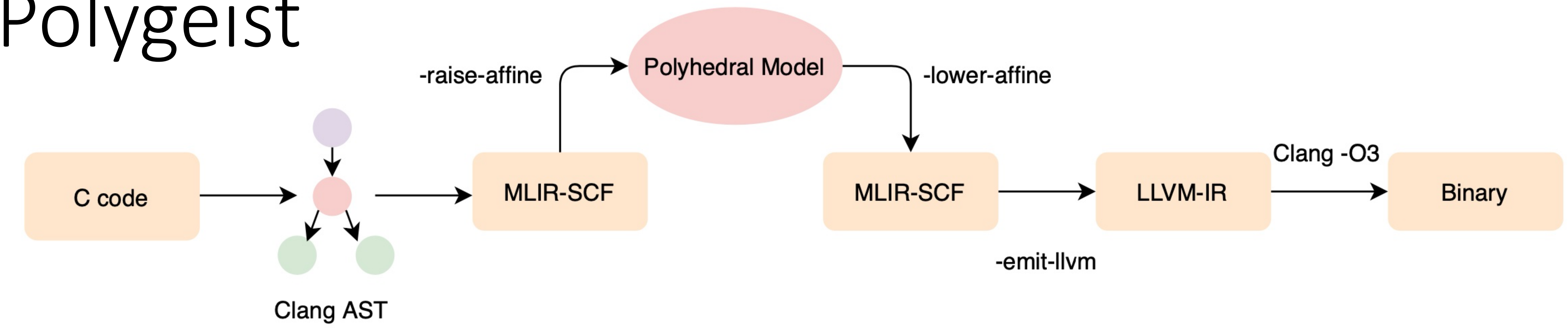
Alex Zinenko

zinenko@google.com

Motivation

- The compiler research has recently been enamored by the MLIR framework, whose first-class polyhedral representation may provide benefits on a variety of codes
- We can fully leverage decades of polyhedral research by connecting MLIR with existing polyhedral tools first.
- Without MLIR-versions of standard polyhedral benchmarks, one cannot perform a fair assessment
- Goal of this work is not to use polyhedral tools to speedup MLIR, but to provide a fair baseline for subsequent work

Polygeist

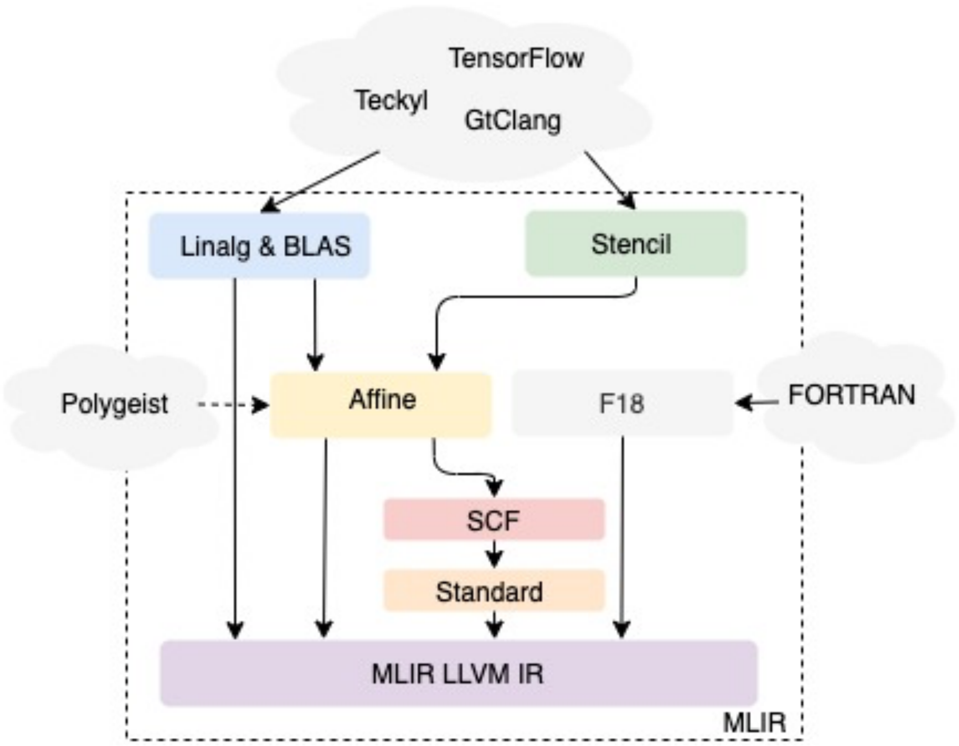


A platform to establish baselines for polyhedral transformations within MLIR

- Generic C or C++ frontend that generates "standard" MLIR
- Raising transformations for transforming "standard" MLIR to polyhedral MLIR (Affine)
- Embedding of existing polyhedral tools (Pluto, CLooG) into MLIR
- Polyhedral benchmarks for MLIR based off of Polybench
- End-to-end evaluation on standard polyhedral benchmarks

The MLIR Framework

- A toolkit for representing and transforming "code"
  - Modular and extensible via dialects (namespaces of operations/types and attributes)
  - Non-opinionated – choose the level of abstraction that is right for you
  - State-of-the-art SSA-based compiler technology



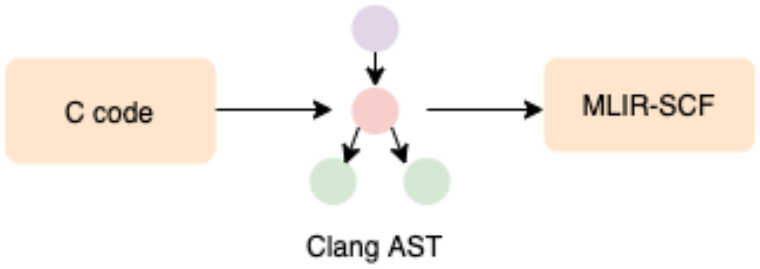

```
%result = "dialect.operation"(%operand, %operand)
           {attribute = #dialect<"value">} ({
^basic_block(%block_argument: !dialect.type):
  "another.operation"() : () -> ()
}) : (!dialect.type) -> !dialect.result_type
```

The Affine dialect

- Represent SCoP with polyhedral-friendly loops and conditions
- Core Affine representation
  - Symbols - parameters
  - Dimensions - symbol extension that accepts induction variables
  - Maps - multi-dimensional function of symbols and dimensions
  - Sets - integer tuples constrained by a conjunction

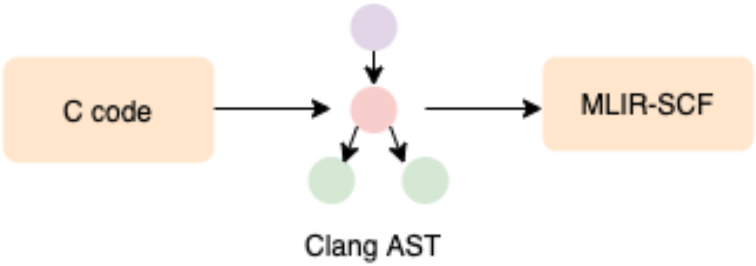
```
%c0 = constant 0 : index
%0 = dim %A, %c0 : memref<?xf32>
%1 = dim %B, %c0 : memref<?xf32>
affine.for %i = 0 to affine_map<()[s0] -> (s0)>()[%0] {
  affine.for %j = 0 to affine_map<()[s0] -> (s0)>()[%1] {
    %2 = affine.load %A[%i] : memref<?xf32>
    %3 = affine.load %B[%j] : memref<?xf32>
    %4 = mulf %2, %3 : f32
    %5 = affine.load %C[%i + %j] : memref<?xf32>
    %6 = addf %4, %5 : f32
    affine.store %6, %C[%i + %j] : memref<?xf32>
  }
}
```

Polygeist Frontend



- Built a generic C or C++ frontend for MLIR, based off of Clang
- C control flow directly lowered to MLIR for, if, etc..
- Variables and arrays represented by MLIR `memref` (memory reference) construct

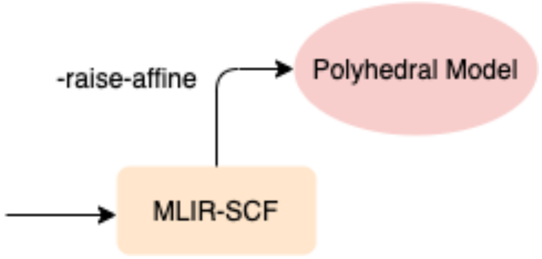
Polygeist Frontend




```
void set(int *arr, int val) {
  #pragma scop
  for(int i=0; i<10; i++){
    arr[2*i] = val;
  }
  #pragma endscop
}
```

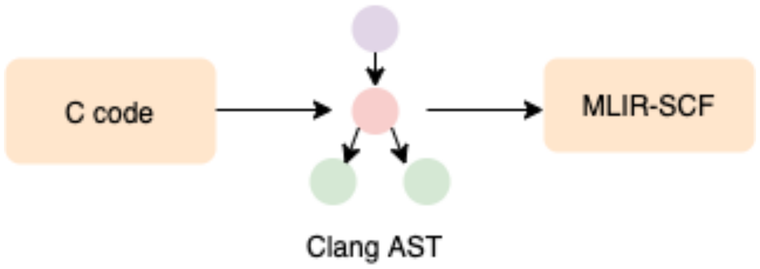
```
func @set(%arg0: memref<?xi32>, %arg1: i32) {
   %c0 = constant 0 : index
   %0 = alloca() : memref<1xmemref<?xi32>>
   store %arg0, %0[%c0] : memref<1xmemref<?xi32>>
   %1 = alloca() : memref<1xi32>
   store %arg1, %1[%c0] : memref<1xi32>
   %c0_i32 = constant 0 : i32
   %c2_i32 = constant 2 : i32
   %c10_i32 = constant 10 : i32
   %2 = index_cast %c10_i32 : i32 to index
   scf.for %arg2 = %c0_i32 to %2 {
     %3 = index_cast %arg2 : index to i32
     %4 = alloca() : memref<1xi32>
     store %3, %4[%c0] : memref<1xi32>
     %5 = load %0[%c0] : memref<1xmemref<?xi32>>
     %6 = load %4[%c0] : memref<1xi32>
     %7 = muli %c2_i32, %6 : i32
     %8 = index_cast %7 : i32 to index
     %9 = load %1[%c0] : memref<1xi32>
     store %9, %5[%8] : memref<?xi32>
   }
   return
 }
```

Polygeist Raising



- Directly lowered constructs are not valid polyhedral programs
- Local variables eliminated, if possible, by new MLIR mem2reg pass
- Loads and stores are raised to affine loads, if possible
  - Detect if index calculation is a valid affine expression
  - Progressively fold index calculation into an affine operation
- if statements are changed to affine if their condition can be raised

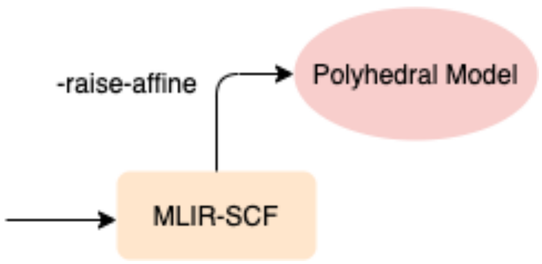
Polygeist Raising




```
func @set(%arg0: memref<?xi32>, %arg1: i32) {
    %c0 = constant 0 : index
    %0 = alloca() : memref<1xmemref<?xi32>>
    store %arg0, %0[%c0] : memref<1xmemref<?xi32>>
    %1 = alloca() : memref<1xi32>
    store %arg1, %1[%c0] : memref<1xi32>
    %c0_i32 = constant 0 : i32
    %c10_i32 = constant 10 : i32
    %2 = index_cast %c10_i32 : i32 to index
    scf.for %arg2 = %c0_i32 to %2 {
      %3 = index_cast %arg2 : index to i32
      %4 = alloca() : memref<1xi32>
      store %3, %4[%c0] : memref<1xi32>
      %5 = load %0[%c0] : memref<1xmemref<?xi32>>
      %c2_i32 = constant 2 : i32
      %6 = load %4[%c0] : memref<1xi32>
      %7 = muli %c2_i32, %6 : i32
      %8 = index_cast %7 : i32 to index
      %9 = load %1[%c0] : memref<1xi32>
      store %9, %5[%8] : memref<?xi32>
    }
    return
  }
```

```
func @set(%arg0: memref<?xi32>, %arg1: i32) {
   affine.for %arg2 = 0 to 10 {
     affine.store %arg1, %arg0[%arg2 * 2]
       : memref<?xi32>
   }
   return
 }
```

Polygeist Raising



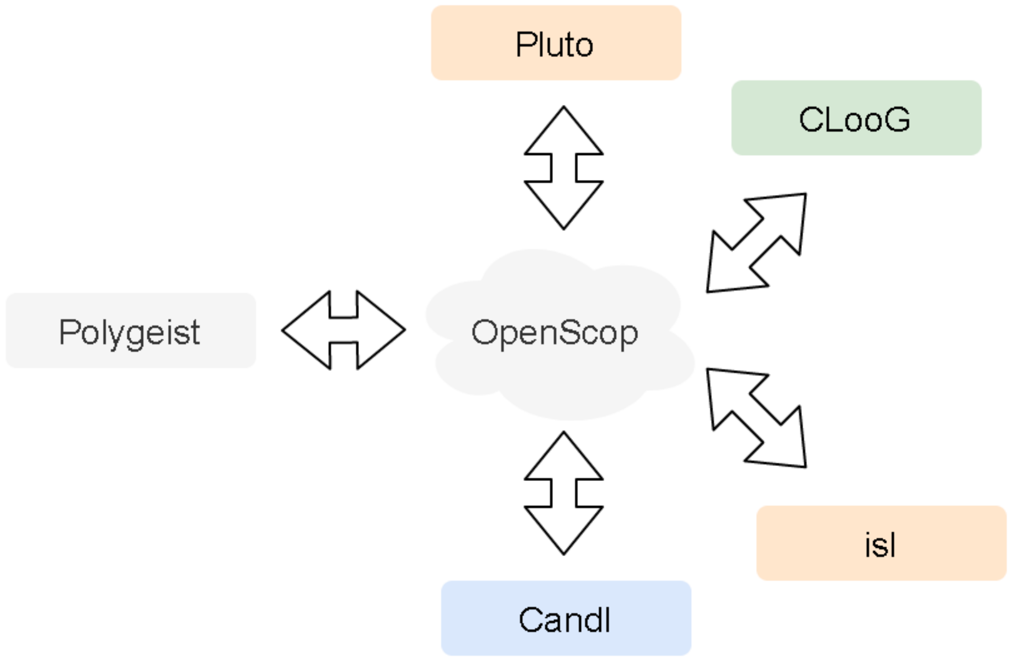
- Select statements must be represented by a C ternary operator
  - C ternaries have lazy-evaluation semantics which are replicated in the generated MLIR
  - Mem2Reg and code motion attempt to remove unnecessary loads within if's to generate a valid select.

```
prefixMax[i] = (prefixMax[i-1] >= data[i])
               ? prefixMax[i-1] : data[i];
```

```
%0 = index_cast %arg2 : i32 to index
%1 = subi %0, %c1 : index
%2 = load %arg0[%1] : memref<?xi32>
%3 = load %arg1[%0] : memref<?xi32>
%4 = cmpi "sgt", %2, %3 : i32
%5 = scf.if %4 -> (i32) {
  %6 = load %arg0[%1] : memref<?xi32>
  scf.yield %6 : i32
} else {
  %6 = load %arg1[%0] : memref<?xi32>
  scf.yield %6 : i32
}
store %5, %arg0[%0] : memref<?xi32>
```

Connecting MLIR to Polyhedral Tools

- Polygeist can obtain polyhedral representation in MLIR Affine
- But it is difficult to leverage existing polyhedral tools
- OpenScop is the interchangeable format among polyhedral tools
- How to translate between MLIR code and OpenScop representation?

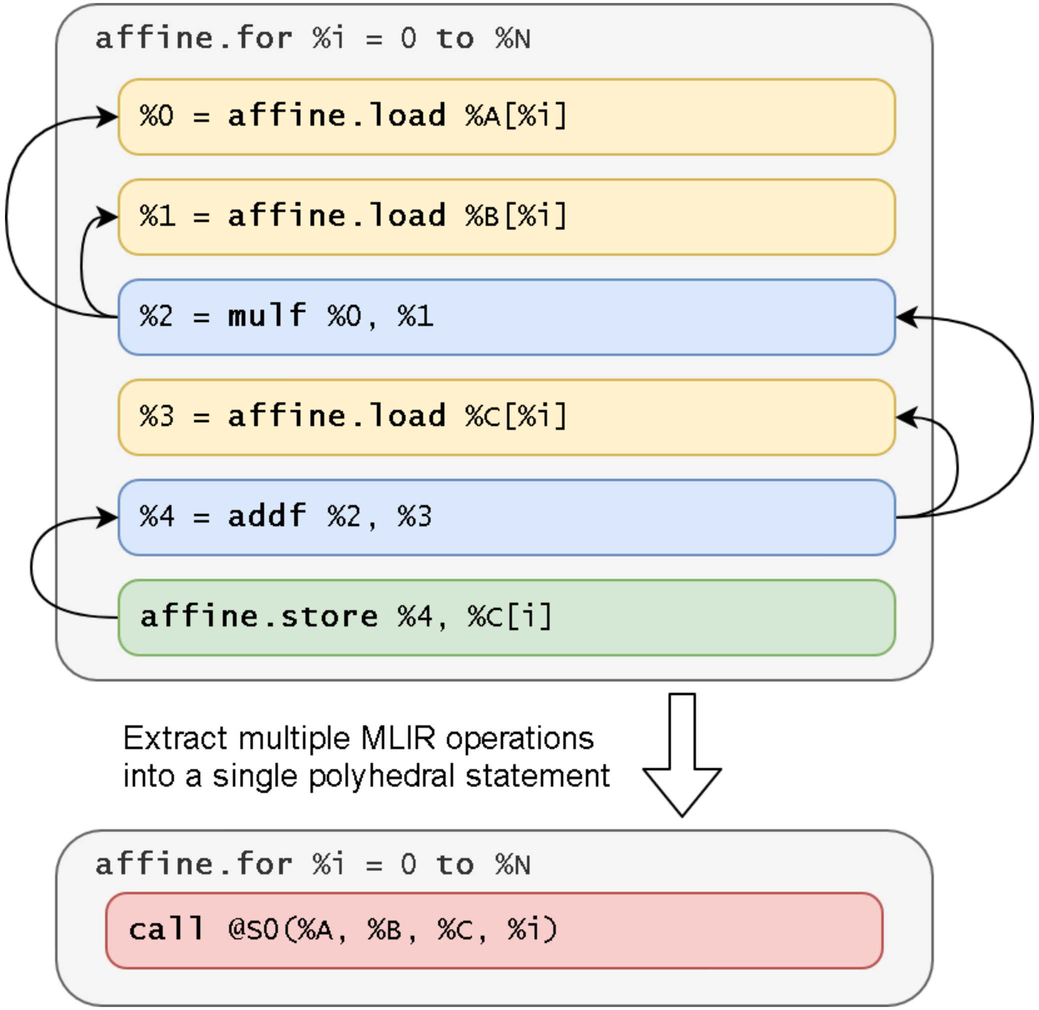


Polyhedral Statement

- OpenScop expects C-like statements:

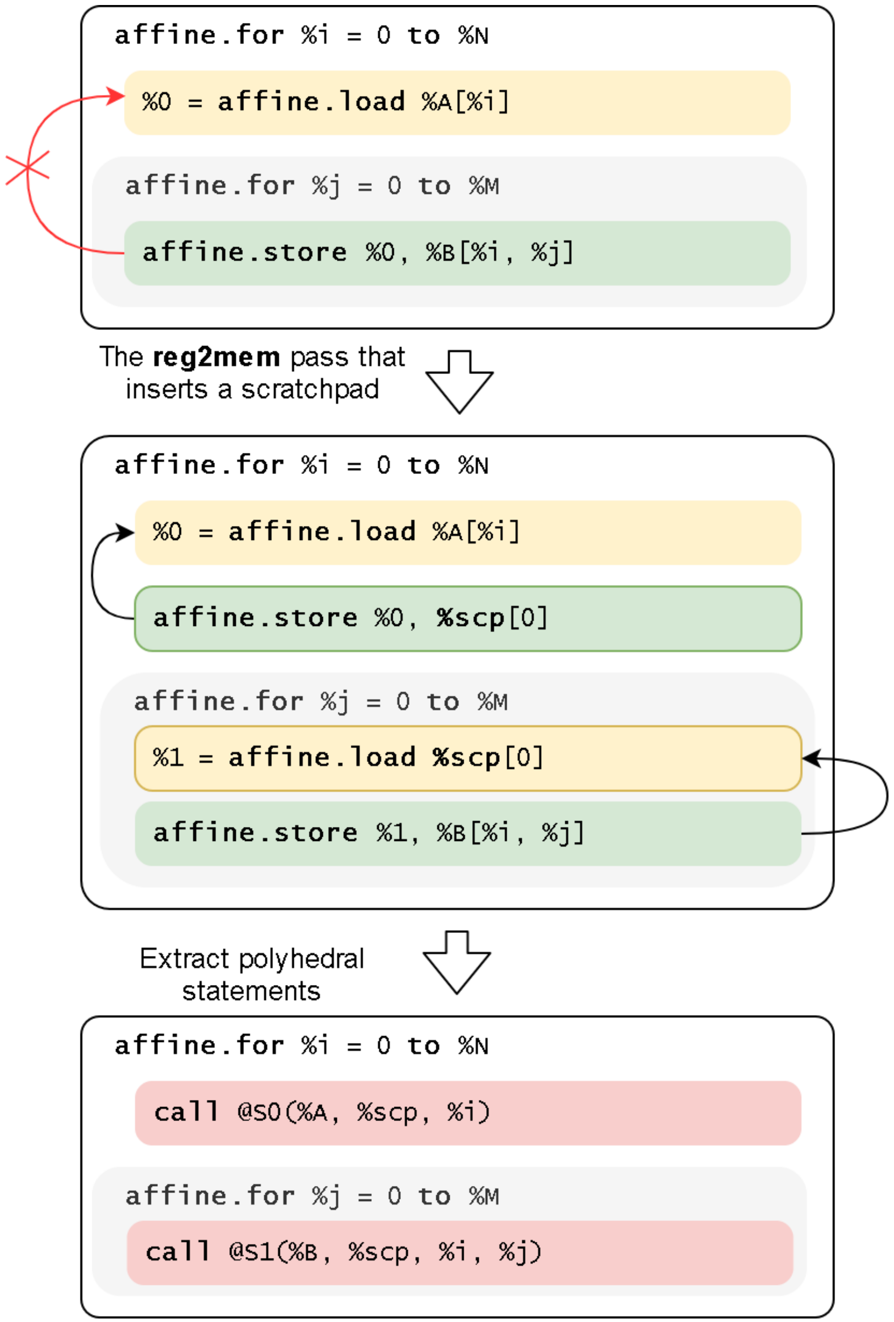
```
C[i][j] += A[i][k] * B[k][j]
```

- MLIR is lower level and a store instruction alone does not specify how to compute the stored operand
- 1 OpenScop statement may correspond to many MLIR operations
- To match C-like statements:
  - Extract 1 MLIR memory write
  - Traverse SSA use-def chains
  - Continue until all operations are loads or symbols



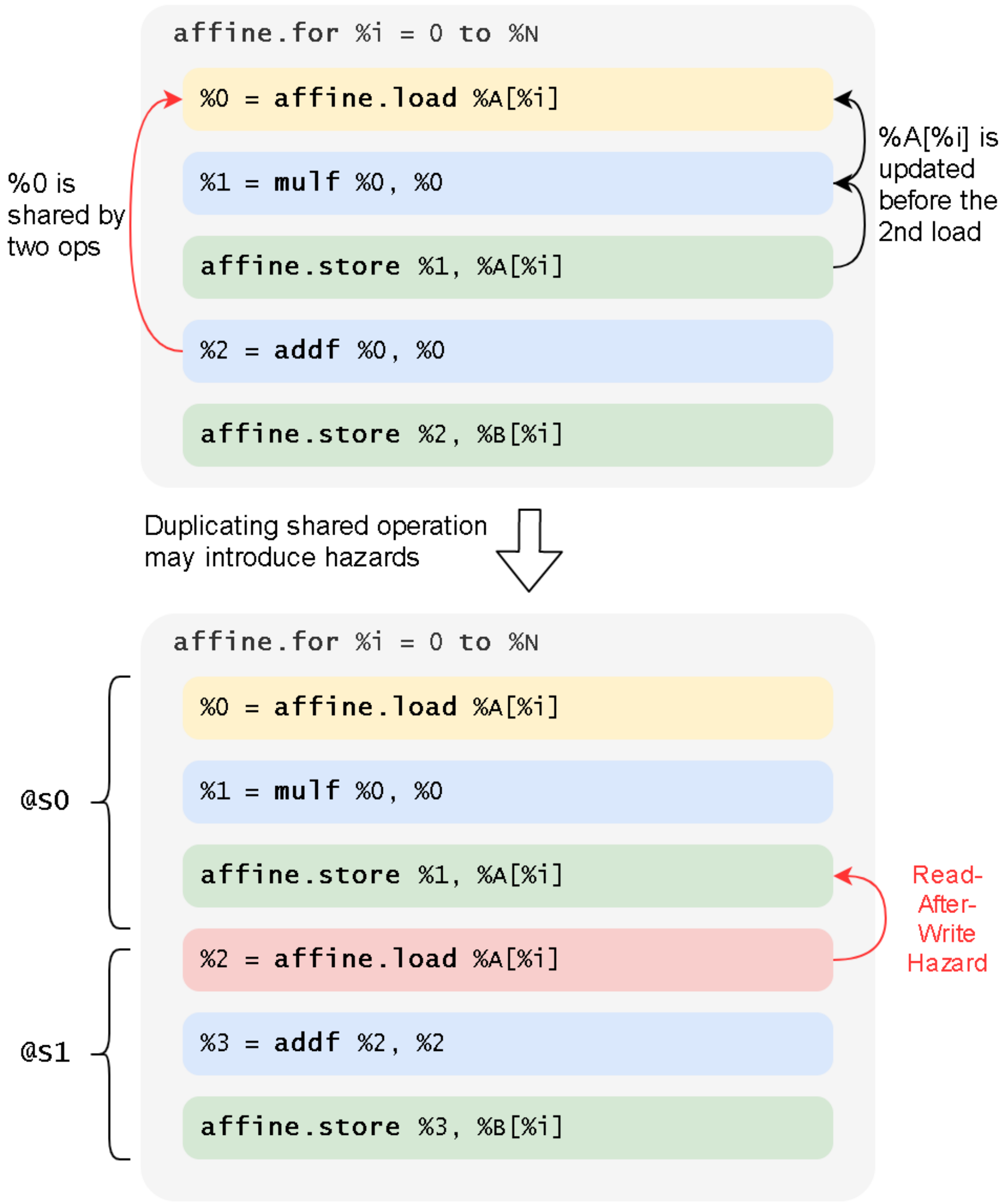
Region-Spanning Problem

- A use-def chain may span multiple loops (regions).
  - e.g., A load op defines a register used by other ops in inner loops.
- Statement nesting in loops is ambiguous
- Difficult to reconstruct when converting back to MLIR
- Reg2mem pass: insert a scratchpad for each use-def across regions



Avoid RAW Hazard

- The RAW hazard problem:
  - A load op is duplicated for use in multiple statements
  - Intermediate writes may clobber
  - After extraction, later statements may load wrong values
- Simplified value analysis to detect
- Insert scratchpads



Outlining

- We outline statements into functions
- Opaque calls with known memory footprints
- Lift local stack allocations and symbol definitions

```
func @S0(%A: memref<?xf32>) {
  %c0 = constant 0 : index
  %s0 = dim %A, %c0 : index
  %1 = affine.load %A[0]
  affine.store %1, %A[symbol(%s0) - 1]
  return
}
```

Lift local symbols to the function interface

```
func @S0(%A: memref<?xf32>, %s0: index ) {
  %0 = affine.load %A[0]
  affine.store %0, %A[%s0 - 1]
  return
}
```

Translate to OpenScop

- First pre-process MLIR Affine code by previous passes
- For each extracted polyhedral statement:
  - Domain: get constraints from affine.for/if
  - Initial Schedule: derive from region nesting and operation order
  - Access: extract from affine load/stores
- Store symbols in OpenScop extensions

Translate to OpenScop

```
affine.for %i = 0 to %N
  affine.for %j = 0 to %N
    call @S0(%A, %i, %j )
```

```
func @S0(%A: memref<?x?xf32>, %i: index,
          %j: index) {
  %0 = affine.load %A[%i, %j]
  %1 = mulf %0, %0
  affine.store %1, %A[%i, %j]
  return
}
```

Domain

```
# e/i | %i   %j  | %N  | 1
   1     1    0     0    0     ## %i >= 0
   1    -1    0     1   -1     ## -%i+%N-1 >= 0
   1     0    1     0    0     ## %j >= 0
   1     0   -1     1   -1     ## -%j+%N-1 >= 0
```

Scattering

```
# e/i| s1   s2   s3   s4   s5  |%i   %j  | %N | 1
  0   -1    0    0    0    0    0    0    0    0
  0    0   -1    0    0    0    1    0    0    0
  0    0    0   -1    0    0    0    0    0    0
  0    0    0    0   -1    0    0    1    0    0
  0    0    0    0    0   -1    0    0    0    0
```

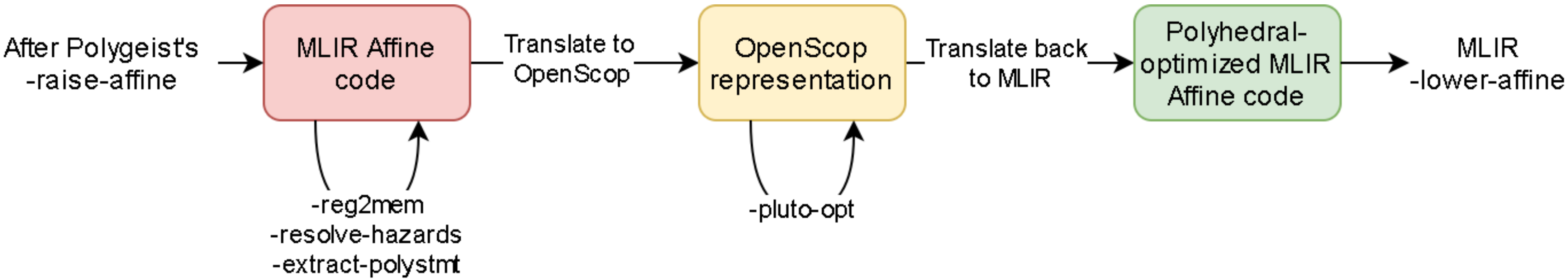
READ/WRITE Accesses

```
# e/i| Arr  [1]  [2] |%i   %j  | %N | 1
  0   -1    0    0    0    0    0    0      ## %A
  0    0   -1    0    1    0    0    0      ## %i
  0    0    0   -1    0    1    0    0      ## %j
```

Regenerate MLIR Code

- Obtain a CLooG AST from an optimized OpenScop representation
- Regenerate MLIR code by traversing AST
- OpenScop symbols will be translated to MLIR values or operations based on a maintained symbol table.

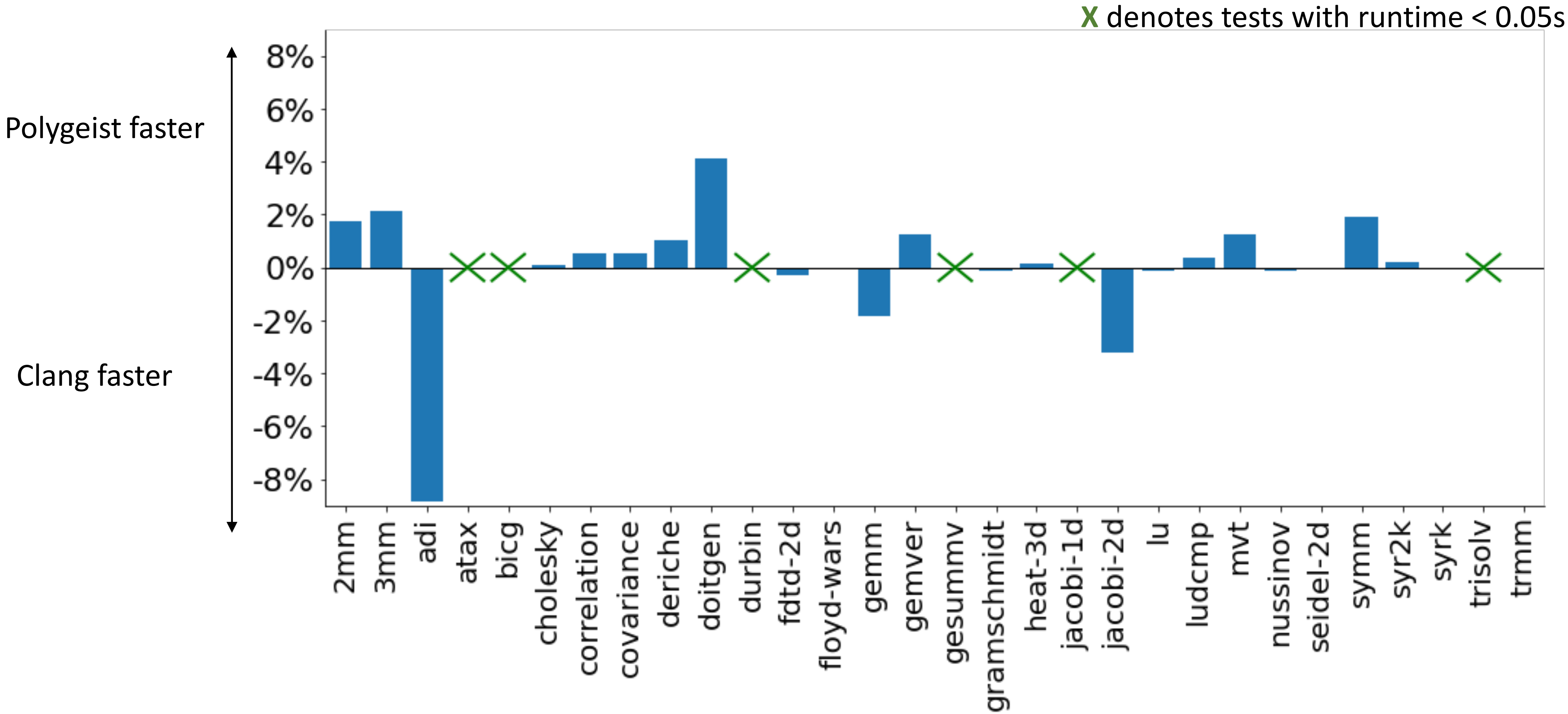
Polyhedral Optimization Pipeline



Evaluation

- Compare Polygeist frontend with Clang
- Compare Polygeist polyhedral optimization with native Pluto

Frontend Comparison with Clang



Frontend Performance Differences

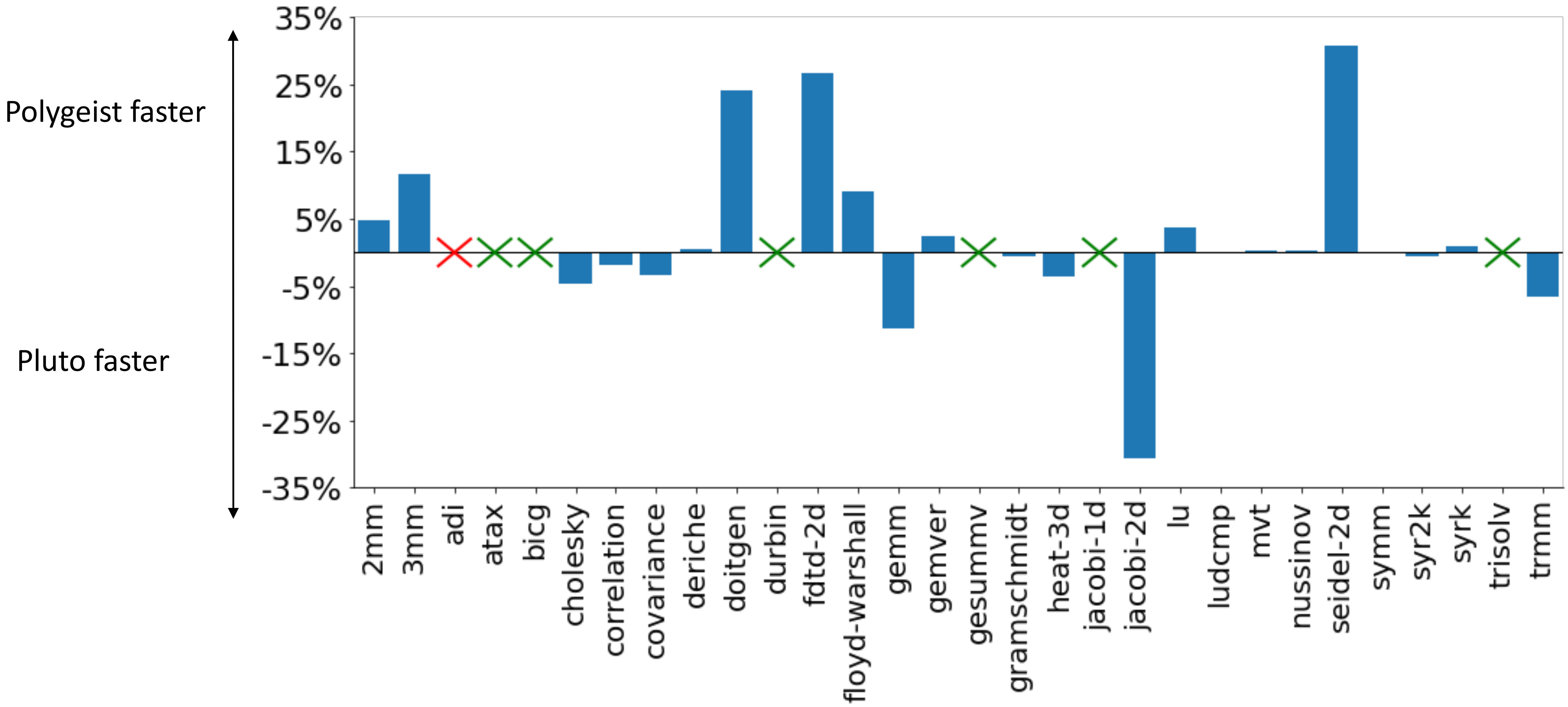
- Solved differences (removed prior to benchmarking):
  - 8% performance boost on Floyd-Warshall occurs if Polygeist generates a single MLIR module for both benchmarking and timing code by default
  - MLIR doesn't properly generate LLVM datalayout, preventing vectorization for MLIR-generated code (patched in our lowering)

Frontend Performance Differences

- Remaining gaps:
  - Different memory allocation function
    - ~48% of gap in adi benchmark
  - LLVM strength-reduction is fragile and sometimes misses reversed loop induction variable (remaining gap in adi)
  - Type of induction variables (MLIR index vs C int32) make it easier for LLVM loop analyses to analyze code generated from MLIR.

Polygeist vs Pluto

Red X denotes test incompatible with Pluto (PET failed)
Green X denotes tests with runtime < 0.05s



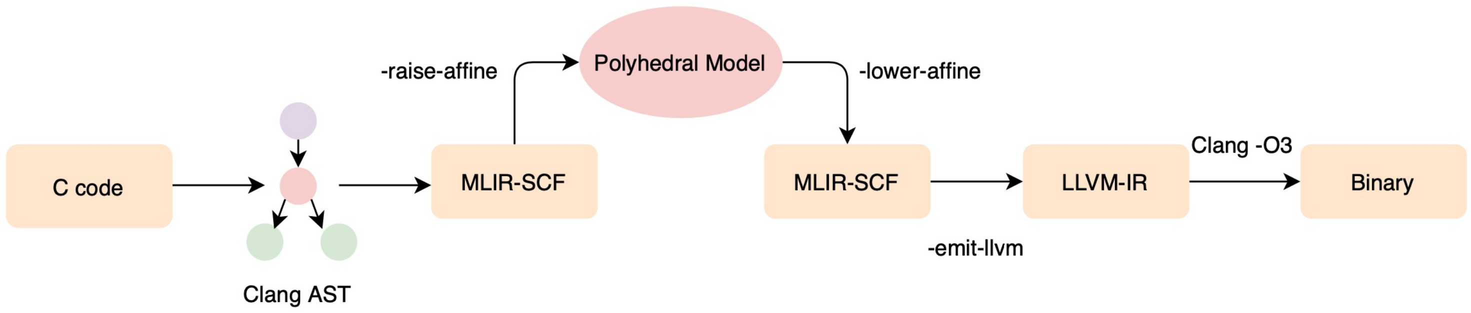
Polyhedral Performance Differences

Besides previously mentioned issues:

- CLooG AST generation
  - We test Pluto by its CLI tool (polycc)
  - Polygeist uses libpluto's `pluto_schedule_prog` API together with CLooG
  - Pluto configure options & optimized schedules are identical between them
  - Different CLooG AST, e.g., 579 (Pluto) vs 78 (Polygeist) lines for jacobi-2d
  - Pluto CLI has finer-grained control over CLooG AST generation
- Induction variable types (Pluto int vs MLIR i64)
- Auto-vectorization triggered differently

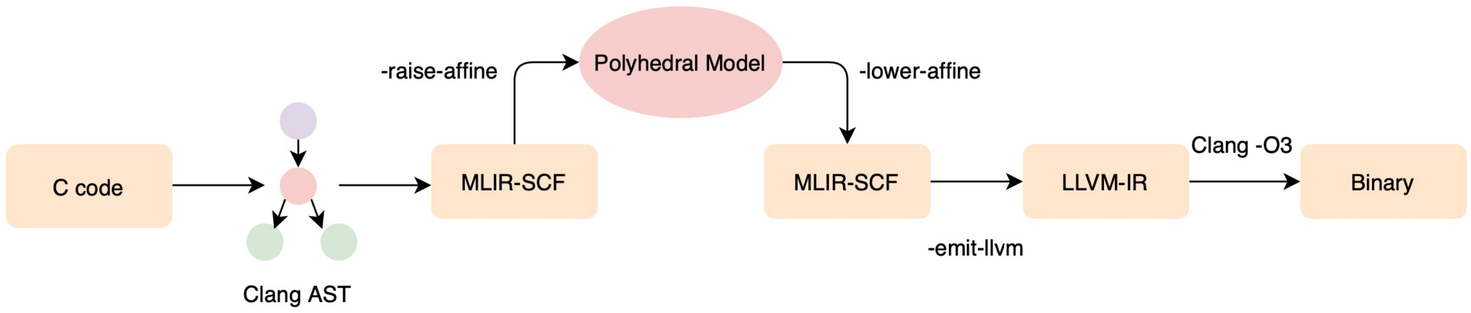
More details in IMPACT paper

Conclusion



- Polygeist provides tools to fairly compare MLIR-based polyhedral flows with prior Polyhedral tools
  - C or C++ frontend for (Affine) MLIR
  - Integration of existing polyhedral tools for transforming MLIR
  - End-to-end comparison using existing Polyhedral benchmarks (Polybench)
- Polygeist enables future research on polyhedral MLIR transformations
- MLIR-based frontend differs from Clang by 1.25%
- Polygeist's polyhedral optimized code differs from Pluto by 7.76%

Future Work



- Compare pipeline with Polly (LLVM-based polyhedral transformations)

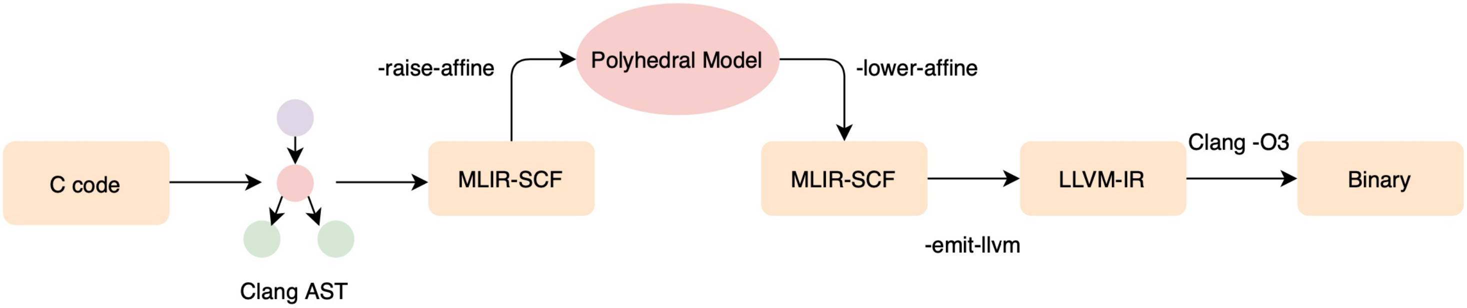
- Use Polyhedral tools to speed up MLIR programs

- Parse existing polyhedral, CPU, and GPU programs for use in MLIR

Acknowledgements

- Thanks to Valentin Churavy, Albert Cohen, Henk Corporaal, Tobias Grosser, and Charles Leiserson for thoughtful discussions on this work.
- William S. Moses was supported in part by a DOE Computational Sciences Graduate Fellowship, in part by Los Alamos National Laboratories, and in part by the United States Air Force Research Laboratory.
- Lorenzo Chelini is partially supported by the European Commission Horizon 2020
- Ruizhe Zhao is sponsored by UKRI and Corerain Technologies Ltd. The support of the UK EPSRC is also gratefully acknowledged.

Conclusion



- Polygeist provides tools to fairly compare MLIR-based polyhedral flows with prior Polyhedral tools
  - C or C++ frontend for (Affine) MLIR
  - Integration of existing polyhedral tools for transforming MLIR
  - End-to-end comparison using existing Polyhedral benchmarks (Polybench)
- Polygeist enables future research on polyhedral MLIR transformations
- MLIR-based frontend differs from Clang by 1.25%
- Polygeist's polyhedral optimized code differs from Pluto by 7.76%

Backup Slides

```
func @set(%arg0: memref<?xi32>, %arg1: i32) {
   affine.for %arg2 = 0 to 10 {
     affine.store %arg1, %arg0[%arg2 * 2] : memref<?xi32>
   }
   return
 }
```