Polly
Polyhedral Optimizations for LLVM

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Polyhedral today

- Good polyhedral libraries
- Good solutions to some problems (Parallelisation, Tiling, GPGPU)
- Several successfull research projects
- First compiler integrations

but still limited IMPACT.

Can Polly help to change this?

Outline

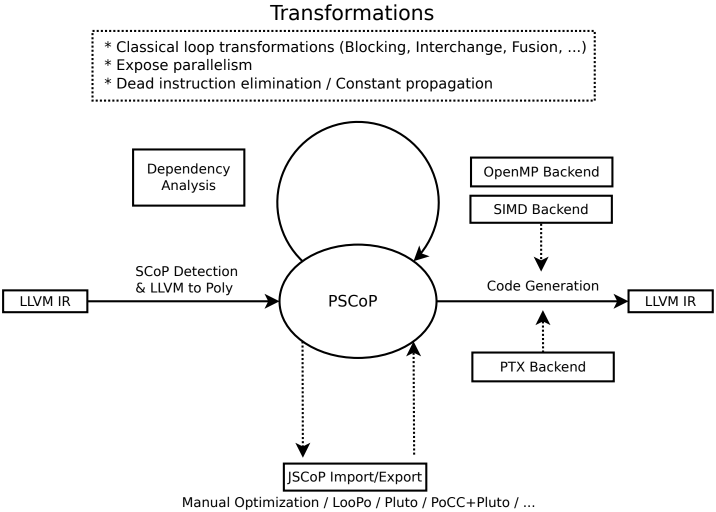
1. LLVM
2. Polly - Concepts & Implementation
3. Experiments
3. Future Work + Conclusion

LLVM

- Compiler Infrastructure
- Low Level Intermediate Language
  - SSA, Register Machine
  - Language and Target Independent
  - Integrated SIMD Support
- Large Set of Analysis and Optimization
- Optimizations Compile, Link, and Run Time
- JIT Infrastructure
- Very convenient to work with

- Classical Compilers:
  - clang → C/C++/Objective-C
  - Mono → .Net
  - OpenJDK → Java
  - dragonegg → C/C++/Fortran/ADA/Go
  - Others → Ruby/Python/Lua
- GPGPU: PTX backend
  OpenCL (NVIDIA, AMD, INTEL, Apple, Qualcomm, ...)
- Graphics Rendering
  (VMWare Gallium3D/LLVMPipe/LunarGlass/Adobe Hydra)
- Web
  - ActionScript (Adobe)
  - Google Native Client
- HLS (C-To-Verilog, LegUp, UCLA - autoESL)
- Source to Source: LLVM C-Backend

The Architecture



Transformations

* Classical loop transformations (Blocking, Interchange, Fusion, ...)
* Expose parallelism
* Dead instruction elimination / Constant propagation

Dependency Analysis

OpenMP Backend

SIMD Backend

LLVM IR

SCoP Detection & LLVM to Poly

PSCoP

Code Generation

LLVM IR

PTX Backend

JSCoP Import/Export

Manual Optimization / LooPo / Pluto / PoCC+Pluto / ...

The SCoP - Classical Definition

```
for i = 1 to (5n + 3)
    for j = n to (4i + 3n + 4)
        A[i-j] = A[i]
    if i < (n - 20)
        A[i+20] = j
```

- Structured control flow
    - Regular for loops
    - Conditions
- Affine expressions in:
    - Loop bounds, conditions, access functions
- Side effect free

AST based frameworks

What about:

- Goto-based loops
- C++ iterators
- C++0x foreach loop

Common restrictions

- Limited to subset of C/C++
- Require explicit annotations
- Only canonical code
- Correct? (Integer overflow, Operator overloading, ...)

Semantic SCoP

Thanks to LLVM Analysis and Optimization Passes:

SCoP - The Polly way

- Structured control flow
    - ~~Regular for loops~~ → Anything that acts like a regular for loop
    - Conditions
- ~~Affine expressions~~ → Expressions that calculate an affine result
- Side effect ~~free~~ known
- Memory accesses ~~through arrays~~ → Arrays + Pointers

Valid SCoPs

do..while loop

```
i = 0;

do {
    int b = 2 * i;
    int c = b * 3 + 5 * i;
    A[c] = i;
    i += 2;
} while (i < N);
```

pointer loop

```
int A[1024];

void pointer_loop () {
    int *B = A;
    while (B < &A[1024]) {
        *B = 1;
        ++B;
    }
}
```

Polyhedral Representation - SCoP

- SCoP = (Context, [Statement])
- Statement = (Domain, Schedule, [Access])
- Access = $(\text{“}\mathit{read}\text{”} | \text{“}\mathit{write}\text{”} | \text{“}\mathit{may\_write}\text{”}, \mathit{Relation})$

Interesting:

- Data structures are integer sets/maps
- Domain is read-only
- Schedule can be partially affine
- Access is a relation
- Access can be may_write

Applying transformations

- $\mathcal{D} = \{Stmt[i,j] : 0 <= i < 32 \wedge 0 <= j < 1000\}$
- $\mathcal{S} = \{Stmt[i,j] \rightarrow [i,j]\}$

- $\mathcal{S}' = \mathcal{S}$

```
for (i = 0; i < 32; i++)
  for (j = 0; j < 1000; j++)
    A[i][j] += 1;
```

Applying transformations

- $\mathcal{D} = \{Stmt[i,j] : 0 <= i < 32 \wedge 0 <= j < 1000\}$
- $\mathcal{S} = \{Stmt[i,j] \to [i,j]\}$
- $\mathcal{T}_{Interchange} = \{[i,j] \to [j,i]\}$

- $\mathcal{S}' = \mathcal{S} \circ \mathcal{T}_{Interchange}$

```
for (j = 0; j < 1000; j++)
  for (i = 0; i < 32; i++)
    A[i][j] += 1;
```

Applying transformations

- $\mathcal{D} = \{Stmt[i,j] : 0 <= i < 32 \wedge 0 <= j < 1000\}$
- $\mathcal{S} = \{Stmt[i,j] \rightarrow [i,j]\}$
- $\mathcal{T}_{Interchange} = \{[i,j] \rightarrow [j,i]\}$
- $\mathcal{T}_{StripMine} = \{[i,j] \rightarrow [i,jj,j] : jj \mod 4 = 0 \wedge jj <= j < jj + 4\}$
- $\mathcal{S}' = \mathcal{S} \circ \mathcal{T}_{Interchange} \circ \mathcal{T}_{StripMine}$

```
for (j = 0; j < 1000; j++)
  for (ii = 0; ii < 32; ii+=4)
    for (i = ii; i < ii+4; i++)
      A[i][j] += 1;
```

JSCoP - Exchange format

Specification:

- Representation of a SCoP
- Stored as JSON text file
- Integer Sets/Maps use ISL Representation

Benefits:

- Can express modern polyhedral representation
- Can be imported easily (JSON bindings readily available)
- Is already valid Python

JSCoP - Example

```
{
"name": "body => loop.end",
"context": "[N] -> { []: N >= 0 }",
"statements": [{
  "name": "Stmt",
  "domain": "[N] -> { Stmt[i0, i1] : 0 <= i0, i1 <= N }",
  "schedule": "[N] -> { Stmt[i0, i1] -> scattering[i0, i1] }",
  "accesses": [{
    "kind": "read",
    "relation": "[N] -> { Stmt[i0, i1] -> A[o0] }"
  },
  {
    "kind": "write",
    "relation": "[N] -> { Stmt[i0, i1] -> C[i0][i1] }"
  }]
}]
}
```

Optimized Code Generation

- Automatically detect parallelism,
- after code generation
- Automatically transform it to:
  - OpenMP, if loop
    - is parallel
    - is not surrounded by any other parallel loop
  - Efficient SIMD instructions, if loop
    - is innermost
    - is parallel
    - has constant number of iterations

Generation of Parallel Code

```
for (i = 0; i < N; i++)
|
| for (j = 0; j < N; j++)
| | for (kk = 0; kk < 1024; kk++)
| | | for (k = kk; k < kk+4; k++)
| | | | A[j][k] += 9;
|
|
| for (j = 0; j < M; j++)
| | B[i] = B[i] * i;
```

Generation of Parallel Code

```
for (i = 0; i < N; i++)
|  S = {[i, 0, j, ...] : 0 <= i, j < N}
|  for (j = 0; j < N; j++)
|  | for (kk = 0; kk < 1024; kk++)
|  | | for (k = kk; k < kk+4; k++)
|  | | | A[j][k] += 9;
|
|  S = {[i, 1, j, ...] : 0 <= i, j < N}
|  for (j = 0; j < M; j++)
|  | B[i] = B[i] * i;
```

Generation of Parallel Code

```
for (i = 0; i < N; i++)
| #pragma omp parallel
| for (j = 0; j < N; j++)
| | for (kk = 0; kk < 1024; kk++)
| | | for (k = kk; k < kk+4; k++)
| | | | A[j][k] += 9;
|
|
| for (j = 0; j < M; j++)
| | B[i] = B[i] * i;
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Generation of Parallel Code

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| for (j = 0; j < M; j++)
| | B[i] = B[i] * i;
```
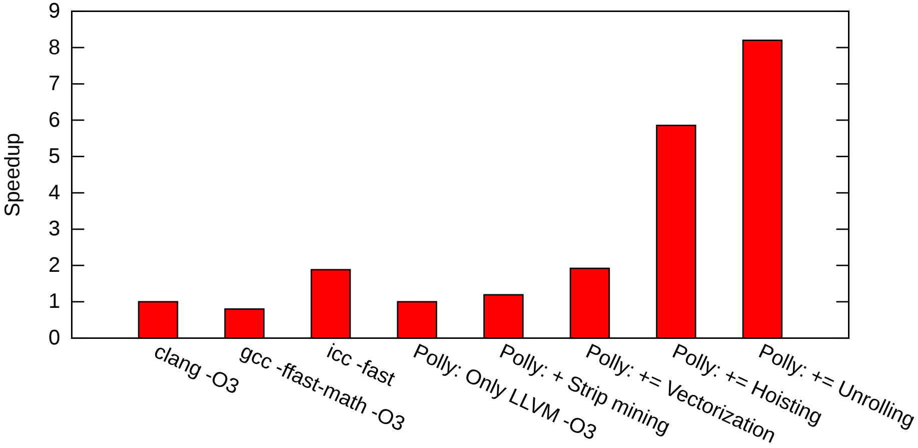

Generation of Parallel Code

```
for (i = 0; i < N; i++)
| #pragma omp parallel
| for (j = 0; j < N; j++)
| | for (kk = 0; kk < 1024; kk++)
| | |
| | | A[j][kk:kk+3] += [9,9,9,9];
|
|
| for (j = 0; j < M; j++)
| | B[i] = B[i] * i;
```

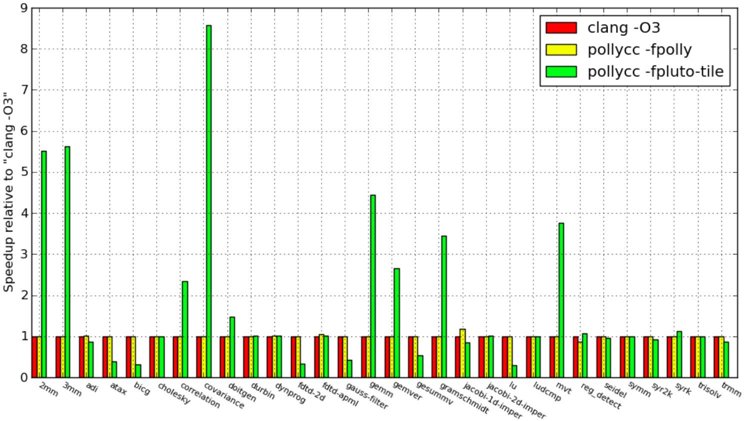
Optimizing of Matrix Multiply



32x32 double, Transposed matric Multiply, C[i][j] += A[k][i] * B[j][k];

Intel® Core® i5 @ 2.40GH, polly and clang from 23. March 2011

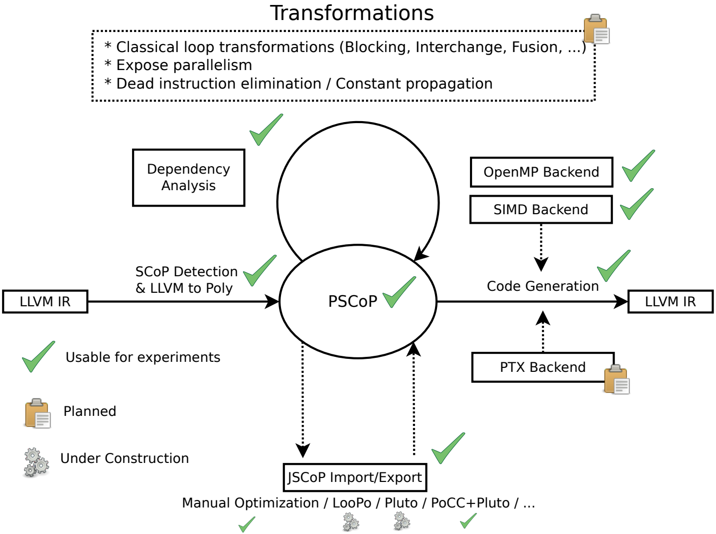
Pluto Tiling on Polybench



Polybench 2.0 (large data set), Intel® Xeon® X5670 @ 2.93GH

polly and clang from 23. March 2011

Current Status



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✓ Usable for experiments

📋 Planned

⚙ Under Construction

Future Work

- Increase general coverage
- Expose more SIMDization opportunities
- Modifieable Memory Access Functions
- GPU code generation

Polly - Conclusion

- Automatic SCoP Extraction
- Non canonical SCoPs
- Modern Polyhedral Representation
- JSCoP - Connect External Optimizers
- OpenMP/SIMD/PTX backends

What features do we miss to apply YOUR optimizations?

http://wiki.llvm.org/Polly