Polyhedral Transformations of Explicitly Parallel Programs

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1. Introduction
2. Explicit Parallelism and Motivation
3. Our Approach
4. Preliminary Results
5. Related Work
6. Conclusions, Future work and Acknowledgments

Introduction

- Software with explicit parallelism is on rise
- Two major compiler approaches for program optimizations
  - AST-based
  - Polyhedral-based
- Past work on transformations of parallel programs using AST-based approaches
  - E.g., [Nicolau et.al 2009], [Nandivada et.al 2013]

- **Polyhedral frameworks** for analysis and transformations of **explicitly parallel** programs ??

Introduction

- Explicit parallelism is different from sequential execution
    - Partial order instead of total order
    - No execution order among parallel portions → no dependence

- For the compiler, explicit parallelism can mitigate imprecision that accompanies unanalyzable data accesses from a variety of sources.
    - Unrestricted pointer aliasing
    - Unknown function calls
    - Non-affine constructs
        - Non-affine expressions in array subscripts
        - Indirect array subscripts
        - Non-affine loop bounds
        - Use of Structs

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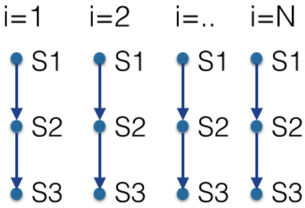
Explicit Parallelism

- Logical parallelism is a specification of a **partial order**, referred to as a **happens-before** relation
    - HB(S1, S2) = *true* ↔ S1 must happen before S2
- Currently, we focus on explicitly parallel programs that satisfy **serial-elision** property
    - Doall parallelism
    - Doacross parallelism

Explicit Parallelism - Doall (OpenMP)

- In case of OpenMP, **Doall** parallelism is equivalent to the **parallel for** clause.
- Happens-before relations exist only among statements in the same iteration
    - Guarantees no cross-iteration dependence

```
#pragma omp parallel for
    for (i-loop) {
            S1;
            S2;
            S3;
    }
```



Explicit Parallelism - Doall (OpenMP) - Example

- LU Decomposition - Rodinia benchmarks [Shuai et.al 09]

```
    for (i = 0; i < size; i++) {
        #pragma omp parallel for
        for (j = i; j < size; j++) {
            #pragma omp parallel for reduction(+:a)
            for (k = 0; k < i; k++) {
                a[i*size+j] -= a[i*size+k] * a[k*size+j];
            }
        }
      ....
    }
```

- `j,k-loops` are annotated as parallel loops and `k-loop` is parallel with a reduction on array a
- Poor spatial locality because of access pattern `k*size+j` for array a
- With happens-before relations from **doall**, loop permutation can be applied to improve spatial locality.

Explicit Parallelism - Doall (OpenMP) - Example

- Permuted kernel

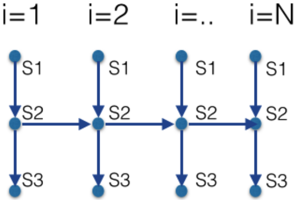
```
        for (i = 0; i < size; i++) {
            #pragma omp parallel for reduction(+:a) private(j)
            for (k = 0; k < i; k++) {
                for (j = i; j < size; j++) {
                    a[i*size+j] -= a[i*size+k] * a[k*size+j];
                }
            }
            ....
         }
```

- 1.25X performance on Intel Xeon Phi coprocessor with 228 threads and input size as 2K
- Array subscripts are non-affine (but can be made affine with delinearization and perform permutation) [Tobias et.al 15]

Explicit Parallelism - Doacross (OpenMP)

- In case of OpenMP, **Doacross** parallelism is equivalent to proposed extension [Shirako et.al 13] to the **ordered** clause (appears in OpenMP 4.1).
- To specify cross-iteration dependences of a parallelized loop

```
#pragma omp parallel for ordered(1)
      for (i-loop) {
        S1;
#pragma omp ordered depend(sink: i-1)
        S2;
#pragma omp ordered depend(source: i)
        S3;
     }
```



Explicit Parallelism - Doacross (OpenMP) - Example

```
// Assume array A is a nested array
#pragma omp parallel for ordered(3)
for (t = 0; t <= _PB_TSTEPS - 1; t++) {
  for (i = 1; i<= _PB_N - 2; i++) {
    for (j = 1; j <= _PB_N - 2; j++) {
#pragma omp ordered  depend(sink: t,i-1,j+1) depend(sink: t,i,j-1) \
     depend(sink: t-1,i+1,j+1)
      A[i][j] = (A[i-1][j-1] + A[i-1][j] + A[i-1][j+1] + A[i][j-1]
               + A[i][j] + A[i][j+1] + A[i+1][j-1] + A[i+1][j]
               + A[i+1][j+1]) / 9.0;
#pragma omp ordered depend(source: t,i,j)
    }
  }
}
```

- 2-dimensional 9 point Gauss Seidel computation - [PolyBench]
- Annotated as 3-D Doacross loop nest
- Even though loop nest has affine accesses, C's unrestricted aliasing semantics for nested arrays can prevent a sound compiler analysis from detecting exact cross iteration dependences.

Explicit Parallelism - Doacross (OpenMP) - Example

```
// Assume array A is a nested array
#pragma omp parallel for ordered(3)
for (t = 0; t <= _PB_TSTEPS - 1; t++) {
  for (i = 1; i<= _PB_N - 2; i++) {
    for (j = 1; j <= _PB_N - 2; j++) {
#pragma omp ordered  depend(sink: t,i-1,j+1) depend(sink: t,i,j-1) \
     depend(sink: t-1,i+1,j+1)
      A[i][j] = (A[i-1][j-1] + A[i-1][j] + A[i-1][j+1] + A[i][j-1]
               + A[i][j] + A[i][j+1] + A[i+1][j-1] + A[i+1][j]
               + A[i+1][j+1]) / 9.0;
#pragma omp ordered depend(source: t,i,j)
    }
  }
}
```

- Through cross-iteration dependences via doacross, loop skewing and tiling can be performed to improve both locality and parallelism granularity.
- 2.2X performance on Intel Xeon Phi coprocessor with 228 threads and input for 100 time steps on a 2K X 2K matrix.

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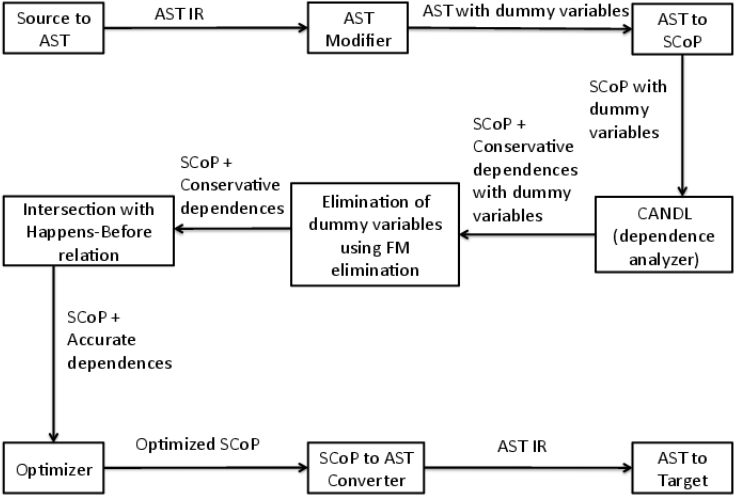
Approach - Idea

- Overestimate dependences based on the sequential order
    - ignore parallel constructs
- Improve dependence accuracy via explicit parallelism
    - obtain happens-before relations from parallel constructs
    - **intersect HB relations with conservative dependences**
- Transformations via polyhedral optimizers
    - PLuTo [Bondhugula et.al 2008]
    - Poly+AST [Shirako et.al 2014]
- Code generation with parallel constructs

- Focus on
    - Doall and Doacross constructs
    - Non-affine subscripts and Indirect arrays subscripts

Algorithm - Framework



Algorithm - Motivation

- Conservative dependence analysis
    - May-information on access range of non-affine array subscripts
- Our existing implementation uses `scoplib` format for convenience (rather than `openscop`)
    - No support for access relations in `scoplib` format (to the best of our knowledge)

- What could potentially represent possible access range of non-affine subscript in polyhedral model?
    - Iterator ?
        - Cannot be part of loops
    - Parameter ?
        - Cannot be loop invariant

Approach - Dummy vector

- Approach use dummy variables to overestimate access range of non-affine subscripts
    - A dummy corresponds to a non-affine expression
    - Compute conservative dependences via dummy variables
- Dummy vector = vector of dummy variables from same scop
- Each dynamic instance of a statement S is uniquely identified by combination of:
    - its iteration vector ($\vec{i_S}$)
    - dummy vector ($\vec{d_S}$)
    - parameter vector ($\vec{p}$)

Approach - Dummy vector - Example

```
int A[N][N], x[N][N], y[N][N];
#pragma omp parallel for
for (i = 0; i < N; i++)
    for (j = 0; j < N; c++)
        A[j][i] = A[ x[j][i] ] [ y[j][i] ];
```

- Non-affine: Two indirect array subscripts (`x[j][i]`, `y[j][i]`)
- Replace non-affine constructs with dummy variables
- Iteration vector ($\vec{i_S}$) = (i, j), Parameter vector ($\vec{p}$) = (N)
- Dummy vector ($\vec{d_S}$) = (dmy_1, dmy_2) = (`x[j][i]`, `y[j][i]`)

Algorithm - Conservative Analysis

- Replace non-affine expressions in array subscripts with `dummy variables` as part of pre-processing
- Create affine inequalities for `dummy variables` based on array declarations and incorporate them into iteration domain
- In case of indirect array subscripts, also associate the index arrays into **read array** list
- Forward the SCoP to CANDL (dependence analyzer)

Algorithm - Conservative Analysis - Example

```
int A[N][N], x[N][N], y[N][N];
#pragma omp parallel for
for (i = 0; i < N; i++)
    for (j = 0; j < N; c++)
        A[j][i] = A[dmy1][dmy2]; // S
```

$$\mathcal{P}_1^{S \to S}(Depth = 1)$$

$$i \leq i' - 1$$

$$j = dmy_1, i = dmy_2$$

$$0 \leq i, j, i', j' \leq (N - 1)$$

$$0 \leq dmy_1, dmy_2 \leq (N - 1)$$

$$0 \leq dmy_1', dmy_2' \leq (N - 1)$$

$$\mathcal{P}_2^{S \to S}(Depth = 2)$$

$$i = i', j \leq j' - 1$$

$$j = dmy_1, i = dmy_2$$

$$0 \leq i, j, i', j' \leq (N - 1)$$

$$0 \leq dmy_1, dmy_2 \leq (N - 1)$$

$$0 \leq dmy_1', dmy_2' \leq (N - 1)$$

Source vector: (i, j, dmy$_1$, dmy$_2$, N)

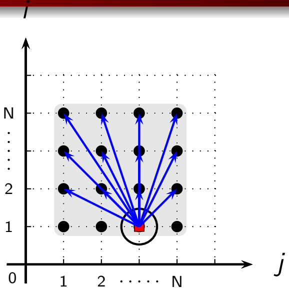
Sink vector: $(i', j', dmy_1', dmy_2', N)$

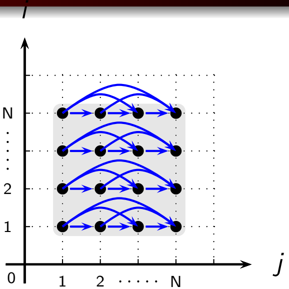
Algorithm - Conservative Analysis - Elimination

After computation of conservative dependences from CANDL, we eliminate dummy variables using Fourier-Motzkin elimination from

- Conservative dependences
- Iteration domain

Algorithm - Conservative Analysis - Elimination - Example





Depth-1 dependences

$$i \leq i' - 1$$

$$\mathcal{P}'^{S\rightarrow S}_{1} : \begin{array}{l} 0 \leq i,j \leq (N-1) \\ 0 \leq i',j' \leq (N-1) \end{array}$$

Depth-2 dependences

$$i = i', j \leq j' - 1$$

$$\mathcal{P}'^{S\rightarrow S}_{2} : \begin{array}{l} 0 \leq i,j \leq (N-1) \\ 0 \leq i',j' \leq (N-1) \end{array}$$

Source vector: (i, j, N)
Sink vector: (i', j', N)

Algorithm - Reflection of happens-before relations

- Let C_d denote happens-before relations on loop at depth $= d$
    - C_d : constraint under which a dependence can exist
- If there are no explicit parallel constructs on a loop, then sequential order would be happens-before relations on that loop
- Happens-before relations in the following program

```
int A[N][N], x[N][N], y[N][N];
#pragma omp parallel for
for (i = 0; i < N; i++)
    for (j = 0; j < N; c++)
        A[j][i] = A[x[j][i]][y[j][i]]; // S
```

$C_1 : \; i = i'$

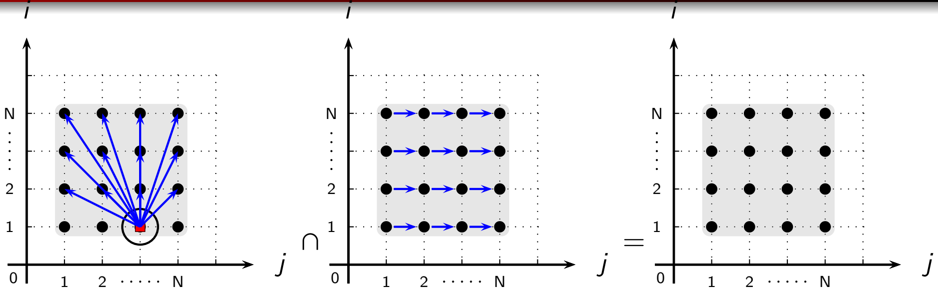
$C_2 : \; i = i', j = j' - 1$

Source vector: (i, j, N) Sink vector: (i', j', N)

Algorithm - Reflection of happens-before relations

```
Input: conservative dependences $\mathcal{P}'$ and constraints $\mathcal{C}$
for each dependence polyhedron ${\mathcal{P}'}_d^{S_i \rightarrow S_j}$ in $\mathcal{P}'$ do
    for each constraint $\mathcal{C}_e^{S_k \rightarrow S_l}$ in $\mathcal{C}$ do
        if $S_i = S_k$ & $S_j = S_l$ & $d = e$ then
            ${\mathcal{P}''}_d^{S_i \rightarrow S_j} := {\mathcal{P}'}_d^{S_i \rightarrow S_j} \cap \mathcal{C}_e^{S_k \rightarrow S_l}$;
        end if
    end for
    Add the reflected polyhedron ${\mathcal{P}''}_d^{S_i \rightarrow S_j}$ to $\mathcal{P}''$;
end for
Output: dependence polyhedra after reflection $\mathcal{P}''$
```

Algorithm - Reflection of happens-before relations - Example - (Depth = 1)



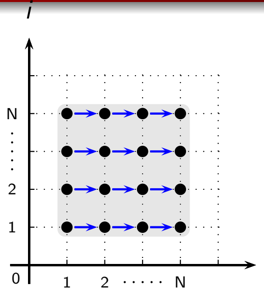
Conservative Dependences
$\mathcal{P}'^{S\rightarrow S}_{1}$:
$i \leq i' - 1$

Happens-Before Relations
$\mathcal{C}'^{S\rightarrow S}_{1}$:
$i = i'$

Final Dependences
$\mathcal{P}''^{S\rightarrow S}_{1}$:
ϕ

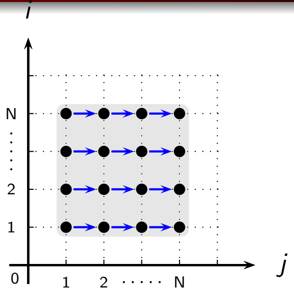
Source vector: (i, j, N) Sink vector: (i', j', N)

Algorithm - Reflection of happens-before relations - Example - (Depth = 2)



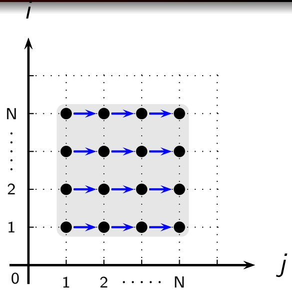
Conservative Dependences $\mathcal{P}'^{S\rightarrow S}_{2}$:
$i = i', j \leq j' - 1$

$\cap$



Happens-Before Relations $\mathcal{C}'^{S\rightarrow S}_{2}$:
$i = i', j = j' - 1$

$=$



Final Dependences $\mathcal{P}''^{S\rightarrow S}_{2}$:
$i = i', j = j' - 1$

Source vector: (i, j, N) Sink vector: (i', j', N)

Algorithm - Code generation

- Transformed kernel after loop permutation

```
int A[N][N], x[N][N], y[N][N];
for (j = 0; j < N; i++)
#pragma omp parallel for
    for (i = 0; i < N; c++)
        A[j][i] = A[x[j][i]][y[j][i]]; // S
```

Algorithm - Implementation

- Implementation is in-progress
- Completed modules:
  - AST Modifier, AST to SCoP converter, Elimination of dummy variables
  - Intersection with Happens-before relations
  - AST to Target
- In-progress modules:
  - Integration with optimizers such as PLuTo, Poly+AST
  - Code generation for do-across

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Rodinia Benchmarks

- Studied 18 explicitly parallel OpenMP-C Rodinia benchmarks
- Identified non-affine constructs used in the benchmarks that limit the use of polyhedral frameworks
  - Indirect Array Subscript (IAS), Non-affine Array Subscript(NAS), Use of Structs (S), Functions (F)
- Potential opportunities for polyhedral loop transformations that can be enabled through our approach
  - Loop permutation, Fusion, Skewing, Tiling, Doacross parallelism, Vectorization

Rodinia Benchmarks

Limitations

Kernel	NAS	IAS	S	F	Transformations
b+ tree		✓	✓		
backprop				✓	perm, fuse, vect
bfs		✓	✓		
cfd	✓			✓	
heartwall				✓	
hotspot	✓				doacross, fuse, skew, tile, vect
kmean				✓	perm, fuse, vect
lavaMD	✓	✓	✓		
leukocyte				✓	fuse, vect

Table: Limitations and possible transformations in Rodinia benchmarks (NAS: Non-affine Array Subscript, IAS: Indirect Array Subscript, S: Struct, F: Function, and perm/fuse/skew/tile/doacross/vect: loop permutation/fusion/skewing/tiling/doacross parallelism/vectorization)

Rodinia Benchmarks (Continued)

Limitations

Kernel	NAS	IAS	S	F	Transformations
lud	✓				perm, vect
mummergpu			✓	✓	
myocyte	✓			✓	
nn	✓			✓	
nw	✓			✓	doacross, skew, perm
particle filter	✓			✓	fuse, vect
path finder					doacross, skew, tile
srad	✓				
streamcluster	✓	✓	✓	✓	

Table: Limitations and possible transformations in Rodinia benchmarks (NAS: Non-affine Array Subscript, IAS: Indirect Array Subscript, S: Struct, F: Function, and perm/fuse/skew/tile/doacross/vect: loop permutation/fusion/skewing/tiling/doacross parallelism/vectorization)

Preliminary results

$$\text{Speedup} = \frac{\text{Exec time of optimized parallel code}}{\text{Exec time of input parallel code}}$$

Kernel	Benchmark	Best Speedup	Transformation
Backprop	Rodinia	28X	Permutation, Vect
Hotspot	Rodinia	2.25X	Skewing, Tiling, Doacross
Lud	Rodinia	1.15X	Permutation, Vect
Particlefilter	Rodinia	1.05X	Fusion

Table: Performance improvements on Intel Xeon Phi with 228 threads[1]

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[1] Some steps (e.g., code gen) were done manually.

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Related Work - Explicitly parallel programs

- Extension of array data-flow analysis to data-parallel and/or task-parallel languages [Collard et.al 96]
- Adaptation of array data-flow analysis to the X10 programs with finish/async parallelism [Yuki et.al 13]
- In these approaches, happens-before relations are first analyzed and data-flow is computed based on the partial order imposed by happens-before relations.

- Our approach first overestimates dependences based on the sequential order and intersect with the happens-before relations from explicitly parallel constructs.
- Our work focuses on transformation of explicitly parallel programs for improved performance where as above works are focused on analysis.

Compile time Approaches for non-affine constructs

- Pugh et.al 91, Maslov et.al 94, ...
- Uses uninterpreted function symbols to represent non-affine constructs
- Generates dependence relations by approximating with affine dependence relations

- We prune conservative dependences using happens-before relations from explicit parallel constructs

Run time Approaches for non-affine constructs

- Doerfert et.al 13, Simburger et.al 14, ...
- Speculative polyhedral optimization techniques, Auto tuning
- Modeling using semi-algebraic sets and real algebra (POLLY)
    - Worst case doubly exponential complexity

- Inspector/ Executor: Strout et.al 03, Basumallik et.al 06, Venkat et.al 14, ...
- Integration into Polyhedral compiler collection chain

- We perform analysis and transformations at compile time

Related Work - PENCIL

- Platform Neutral Compute Intermediate Language
- Automatic parallelization on multi-threaded SIMD hardware for DSL's
- Provides extensions and directives that allow users to supply dependence information

- We are interested in leveraging happens-before relations from programs written in general purpose languages like OpenMP, X10, Habanero-C whereas PENCIL is focused on supporting DSL's in which certain coding rules are enforced related to pointer aliasing, recursion and unstructured control flow.

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Conclusions

- Introduced an approach that reflects **happens-before** relations from explicitly parallel constructs in the dependence polyhedra to mitigate conservative dependence analysis.
- Studied 18 explicitly-parallel OpenMP benchmarks from Rodinia suite.
- Shown that the use of explicit parallelism enables larger set of polyhedral transformations, compared to what might have been possible if the input program was sequential.

Future work and Acknowledgments

- Future work
    - Incorporate additional explicit parallel constructs such as barrier and task parallelism
    - Additional transformations for explicit parallel programs

- Acknowledgments
    - Rice Habanero Extreme Scale Software Research Group
    - IMPACT 2015 chairs, reviewers and shepherd

Backup - Conservative Analysis

- Access relations [Wonnacott thesis] and uninterpreted function symbols [Omega library] could have been used instead of dummy variables, but our implementation is heavily dependent on `scoplib` format instead of `openscop` format.
- Our existing implementation uses `scoplib` format for convenience (rather than `openscop`)
  - No support for access relations in `scoplib` format (to the best of our knowledge)

Backup - References

- Nicolau et.al 2009 : Alexandru Nicolau, Guangqiang Li, Alexander V. Veidenbaum, and Arun Kejariwal. 2009. Synchronization optimizations for efficient execution on multi-cores. In Proceedings of the 23rd international conference on Supercomputing (ICS '09). ACM, New York, NY, USA, 169-180. DOI=10.1145/1542275.1542303 http://doi.acm.org/10.1145/1542275.1542303
- Nandivada et.al 2013 : A Transformation Framework for Optimizing Task-Parallel Programs . V. Krishna Nandivada, Jun Shirako, Jisheng Zhao, Vivek Sarkar. ACM Transactions on Programming Languages and Systems (TOPLAS), Volume 35, May 2013.