Polyhedral Optimizations of Explicitly Parallel Programs (PoPP)

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1. Introduction and Motivation

2. Background

3. Our framework

4. Evaluation

5. Related Work

6. Conclusions and Future work
Introduction - What is it?

- Move towards Exa-scale computing
  - Billions of billions calculations per second
  - Expected to be processing power of human brain at neural level

- Enabling applications to fully exploit them is not easy!

- Then, How??
Enabling applications to fully exploit them is not easy!

Two approaches:

- Automatically parallelize sequential programs using optimizers (PLuTo, PolyAST etc)
  - Easy! But, limitations exist.

- Manually parallelize using explicitly-parallel programming models (Ex: OpenMP, MPI, Habanero, CAF, HPF etc)
  - Tedious! But, we can achieve high performance
Introduction and Motivation

Classical Approach

Automatic parallelization of sequential programs

Input:
Sequential program

Program Analysis

- Loop Nest information
- Control flow
- Array subscripts
- Loop bounds
- Dependence information

Program Transformations

Output:
Optimized program for exploiting “Parallelism” and “Locality” on target machine

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Where is the trend??

- "Parallelism is oblivious; Let programmer expresses logical parallelism in the application and then let compiler do optimizations accordingly" - Charles Leiserson
  - So far, less attention paid!!

- We introduce an end-to-end compiler framework (PoPP) to optimize parallel applications
Optimizations of Explicitly-Parallel Programs

Input:
Parallel program
(preferably with all possible logical parallelism)

Program Analysis

- Loop Nests information
- Control flow
- Array subscripts
- Loop bounds
- Dependence information
- Happens-Before relations

Program Transformations

Output:
Optimized parallel program for exploiting “Parallelism” and “Locality” on target machine
Introduction and Motivation

Motivation - Why do we need?

- Jacobi benchmark (4 point 2D stencil) - OpenMP 4.0 Tasks
- Scalability on Intel (Westmere) with 12 cores
- Comparison with PoPP

![Graph showing speedup vs cores comparison between PoPP + gcc-4.9.2 and gcc-4.9.2. The graph illustrates a linear increase in speedup with cores, with PoPP showing a higher efficiency compared to gcc-4.9.2.]
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Polyhedral Compilation Techniques

- Compilers techniques for analysis and transformation of codes with nested loops
  - Algebraic framework for affine program optimizations
  - Reason about executions (iterations) of statements
  - Dependence analysis for arrays
  - Encode loop transformations
  - Generate transformed code efficiently

```c
for (i = 0; i < N; i++) {
    X[i] = B[i];

    for (j = 0; j < i; j++) {
        X[i] -= L[i][j] * X[j];
    }

    X[i] /= L[i][j];
}
```
1 \textbf{for} (i = 0; i < N; i++) {
2 \textbf{S1:} \quad X[i] = B[i];
4 \textbf{for} (j = 0; j < i; j++) {
5 \textbf{S2:} \quad X[i] \leftarrow L[i][j] \cdot X[j];
8 \textbf{S3:} \quad X[i] /= L[i][j];
}

\textbf{Iteration domain:}

\text{Set of statement instances}

S1(i): \{ i \mid 0 \leq i \leq N \}
S2(i,j): \{ (i,j) \mid 0 \leq i \leq N \& 0 \leq j \leq i \}
S3(i): \{ i \mid 0 \leq i \leq N \}

\textbf{Schedule:}

\text{Logical timestamp}

S1(i): (0, i)
S2(i,j): (0, i, 1, j)
S3(i): (0, i, 2)

\textbf{Access function:}

\text{Data accessed}

S1(i): \{ X[i], B[i] \}
S2(i,j): \{ X[i], X[j], L[i][j] \}
S3(i): \{ X[i], L[i][j] \}
Polyhedral analyzers capture the above dependences into system of equalities and inequalities.
Polyhedral Compilation Techniques - Summary

1 for (i = 0; i < N; i++) {
2   S1: X[i] = B[i];

4   for (j = 0; j < i; j++) {
5     S2: X[i] -= L[i][j] * X[j];
6   }

8   S3: X[i] /= L[i][j];
9 }

- Advantages
  - Precise data dependency computation
  - Unified formulation of complex set of loop transformations

- Limitations
  - Affine array subscripts, static affine control flow
  - But, conservative approaches exist!
Explicit Parallelism

- Major difference b/w Sequential and Parallel programs
  - Sequential programs - Total execution order
  - Parallel programs - Partial execution order

- Loop-level parallelism
  - Loop is annotated with 'omp parallel for'
  - Iterations of the loop can be run in parallel

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

- Major difference b/w Sequential and Parallel programs
  - Sequential programs - Total execution order
  - Parallel programs - Partial execution order

- Task-level parallelism (OpenMP 3.0)
  - Region of code is annotated with 'omp task'
  - Synchronization is annotated with 'omp taskwait'

```c
T1: #pragma omp task
    {S1}
T2: #pragma omp task
    {S2}
Tw: #pragma taskwait
```
Explicit Parallelism

- Major difference b/w Sequential and Parallel programs
  - Sequential programs - Total execution order
  - Parallel programs - Partial execution order

- Task-level parallelism with dependency (OpenMP 4.0)
  - Region of code is annotated with `omp task depend`
  - Synchronization among previously created sibling tasks is achieved by `depend` clauses

1. \( T1: \texttt{#pragma omp task depend} \rightarrow (\text{out: A}) \{ S1 \} \)
2. \( T2: \texttt{#pragma omp task depend} \rightarrow (\text{in: A}) \{ S2 \} \)
3. \( T3: \texttt{#pragma omp task depend} \rightarrow (\text{out: B}) \{ S3 \} \)
Explicit Parallelism

- Happens-Before relations
  - Specification of partial order
  - \( \text{HB}(S_1, S_2) = true \iff S_1 \text{ must happen before } S_2 \)

\[
\text{HB}(S_1 \ (i), S_2(i)) = true
\]

\[
\text{HB}(S_1, S_2) = false
\]

\[
\text{HB}(S_1, S_2) = true
\]
Explicit Parallelism

- **Serial-Elision property**
  - Removal of all parallel constructs results in a sequential program that is a valid (albeit inefficient) implementation of the parallel program semantics.
Explicit Parallelism

- Serial-Elision property
  - Removal of all parallel constructs results in a sequential program that is a valid (albeit inefficient) implementation of the parallel program semantics.

Satisfies

Not Satisfies (Not possible through depend clause)
Introduction and Motivation

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Related Work

Conclusions and Future work
PoPP - Program Analysis

- **Step1**: Overestimate dependences based on the sequential order (Ignore parallel constructs)

```plaintext
1 T1: #pragma omp task depend(out: A)   
   { S1: E[F[...]] = .. }             
2 T2: #pragma omp task depend(in: A)   
   { S2: G[E[...]] = .. }             
3 T3: #pragma omp task depend(in: A)   
   { S3: B[C[...]] = .. }             
```

- Indirect array subscripts
- Difficult to capture precise dependences
- Going conservatively !!
PoPP - Program Analysis

- Step 1: Overestimate dependences based on the sequential order (Ignore parallel constructs)
- Step 2: Compute HB relations

1. T1: #pragma omp task depend(out: A)
2. { S1: E[F[...]] = .. }
3. T2: #pragma omp task depend(in: A)
4. { S2: G[E[...]] = .. }
5. T3: #pragma omp task depend(in: A)
6. { S3: B[C[...]] = .. }

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PoPP - Program Analysis

- Step 1: Overestimate dependences based on the sequential order (Ignore parallel constructs)
- Step 2: Compute HB relations
- Step 3: Intersect 1 & 2 (Gives best of both worlds)

Conservative dependences $\cap$ HB Relations = Refined dependences
Our framework

PoPP - Program Transformations

- Step 4: Use refined dependences to existing optimizers

Refined dependences → Fusion of S1 & S2 for better data locality → Optimized code

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1. **Input**: Explicitly parallel program, $\mathcal{I}$
2. $\mathcal{P} :=$ set of conservative dependences in $\mathcal{I}$
3. $\mathcal{HB} :=$ Transitive closure of happens-before relations from parallel constructs in $\mathcal{I}$
4. $\mathcal{P'} := \mathcal{P} \cap \mathcal{HB}$
5. Optimized schedules, $\mathcal{S} = \text{Transform} (\mathcal{I}, \mathcal{P'})$
6. $\mathcal{I'} = \text{CodeGen} (\mathcal{I}, \mathcal{S}, \mathcal{P'})$
7. **Output**: Optimized explicitly parallel program, $\mathcal{I'}$
PoPP - Transformations & Code Generation

- Transformations - PolyAST framework [Shirako et.al SC’2014]
  - To perform loop optimizations
  - Hybrid approach of polyhedral and AST-based transformations
  - Detects reduction, doacross and doall parallelism from dependences

- Code Generation
  - Doall parallelism - `omp parallel for`
  - Doacross parallelism - `omp doacross`
    - Proposed in OpenMP 4.1 [Shirako et.al IWOMP’11]
    - Allows fine grained synchronization in multidimensional loop nests
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PoPP Evaluation

Two different SMP platforms

<table>
<thead>
<tr>
<th></th>
<th>Intel Xeon 5660 (Westmere)</th>
<th>IBM Power 8E (Power 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Microarch</strong></td>
<td>Westmere</td>
<td>Power PC</td>
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<td><strong>Clock speed</strong></td>
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<td><strong>Cores/socket</strong></td>
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<td><strong>Total cores</strong></td>
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<td><strong>Compiler</strong></td>
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<td>gcc/g++ -4.9.2</td>
</tr>
<tr>
<td><strong>Compiler flags</strong></td>
<td>-O3 -fast(icc)</td>
<td>-O3</td>
</tr>
</tbody>
</table>
Benchmarks

- **KASTORS** - Task parallel benchmarks (3)
  - Jacobi, Jacobi-blocked, Sparse LU
  - OpenMP 4.0 task, task-depend, taskwait constructs

- **RODINIA** - Loop parallel benchmarks (8)
  - Back propagation, CFD solver, Hotspot, Kmeans
  - LUD, Needle-Wunch, Particle filter, Path finder
  - OpenMP 3.0 parallel for, Doacross (Modified) constructs

- **Unanalyzable data access patterns**
  - Non-affine array subscripts
  - Linearized array subscripts
  - Indirect array subscripts
  - Unrestricted pointer aliasing
  - Unknown function calls
PoPP performance on KASTORS Benchmarks - Intel

- Optimization variants
  - Original, PoPP w/o HB, PoPP with HB

Jacobi: F, S, T, D
Jacobi-blocked: F, S, D
Sparse LU: F, D

Intel Westmere with 12 cores
Optimizations: Fusion(F), Skewing(S), Tiling(T), Doacross sync (D)

PoPP improved performance from 3.19X to 9.72X
PoPP performance on KASTORS Benchmarks - IBM

- **Optimization variants**
  - Original, PoPP w/o HB, PoPP with HB

- Jacobi: F, S, T, D
- Jacobi-blocked: F, S, D
- Sparse LU: F, D

IBM Power8 with 24 cores
Optimizations: Fusion(F), Skewing(S), Tiling(T), Doacross sync (D)

PoPP improved performance from 4.13X to 8.97X

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PoPP performance on RODINIA Benchmarks - Intel

- Optimization variants
  - Original, PoPP w/o HB, PoPP with HB

PoPP improved performance from 2.14X to 19.94X
PoPP performance on RODINIA Benchmarks - IBM

- Optimization variants
  - Original, PoPP w/o HB, PoPP with HB

IBM Power8 with 24 cores

- PoPP improved performance from 1.60X to 16.97X
Related Work
Dataflow analysis of explicitly parallel programs

- Extensions to data-parallel/ task-parallel languages [J.F. Collard et.al Europar’96]
- Extensions to X10 programs with async-finish languages [T. Yuki et.al PPoPP’13]

In these approaches, HB relations are analyzed and data-flow is computed based on partial order imposed by HB relations.

We focus on transformations of explicitly parallel programs where as above works only focus in analysis
PENCIL - Platform Neutral Compute Intermediate Language [Baghdadi et.al. PACT’15]
- Automatic parallelization for DSL’s
- Prunes data-dependence relations on parallel loops
- No support for task parallel constructs
- Enforces certain coding rules related to aliasing, recursion etc.

Preliminary approach to optimize parallel programs [Pop and Cohen CPC’10]
- Extract parallel semantics into compiler IR and perform polyhedral optimizations
- Envisaged on considering OpenMP streaming extensions
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Conclusions and Future work

PoPP - Conclusions and Future work

Conclusions: Our approach

- Introduced a new analysis for parallel programs
- Reduced spurious dependences from conservative analysis by intersection with happens-before relations
- Broadened the range of legal transformations for parallel programs

Future work:

- Parallel constructs that don’t satisfy serial-elision property
- Code generation with task constructs

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- Rice Habanero Extreme Scale Software Research Group
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