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 ?

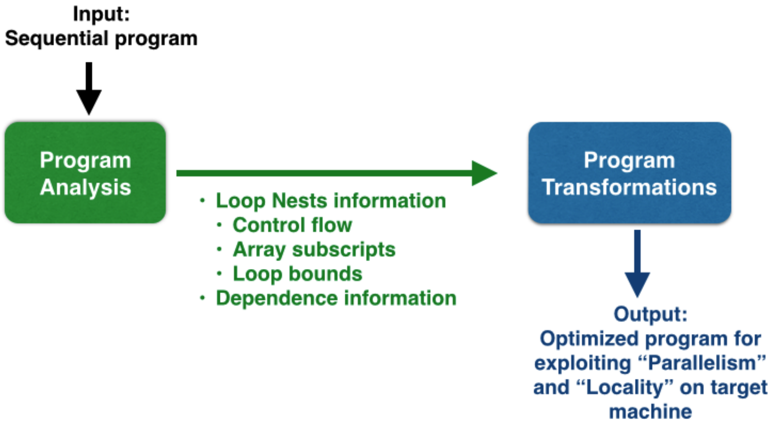
- Move towards Exa-scale computing
  - Billions of billions calculations per second
  - Expected to be processing power of human brain at neural level
- Enabling applications to fully exploit them is not easy !
- Then, How ??

Introduction - What is it ?

- 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

Classical Approach

Automatic parallelization of sequential programs



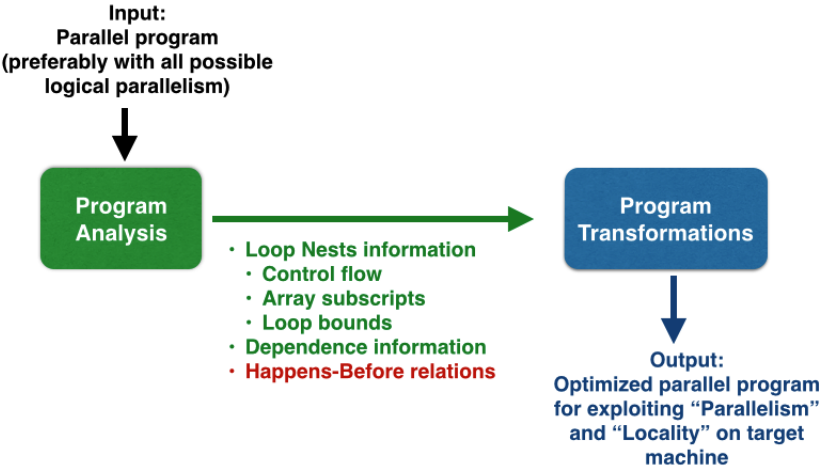
Where is the trend ??

- "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

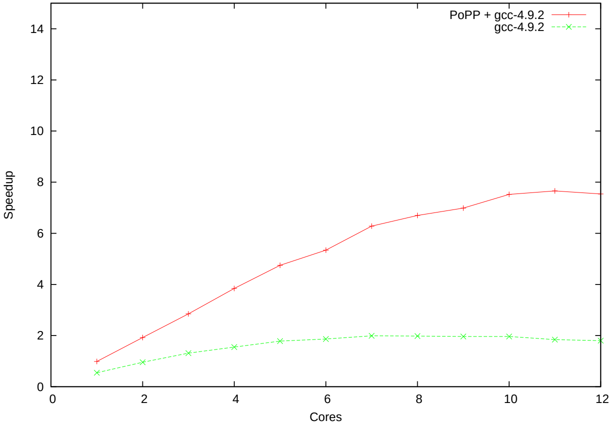
Introduction - What do we do ?

Optimizations of Explicitly-Parallel Programs



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



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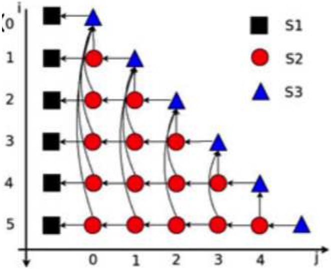
Polyhedral Compilation Techniques

- 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

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

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

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



Polyhedral Compilation Techniques - Representation

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

      for(j = 0; j < i; j++) {
S2:         X[i] -= L[i][j] * X[j];
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S3: X[i] /= L[i][j];
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```
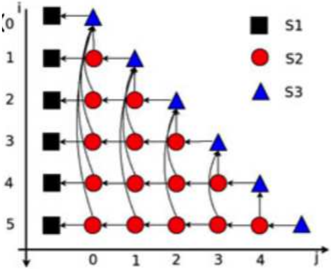



Iteration domain:

Set of statement instances

S1(i): { i | $0 \leq i \leq N$ }

S2(i,j): { (i,j) | $0 \leq i \leq N$ & $0 \leq j \leq i$ }

S3(i): { i | $0 \leq i \leq N$ }

Schedule:

Logical timestamp

S1(i): (0, i)

S2(i,j): (0, i, 1, j)

S3(i): (0, i, 2)

Access function:

Data accessed

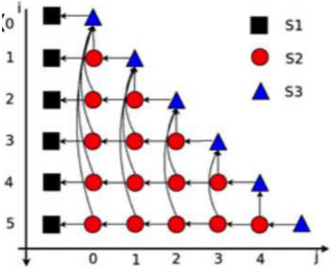
S1(i): { X[i], B[i] }

S2(i,j): { X[i], X[j], L[i][j] }

S3(i): { X[i], L[i][j] }

Polyhedral Compilation Techniques - Dependences

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

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

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



Dependence b/w S1 & S2

Ex: S1(1) ← S2(1,0)

Dependence b/w S2 & S3

Ex: S2(2,1) ← S3(2)

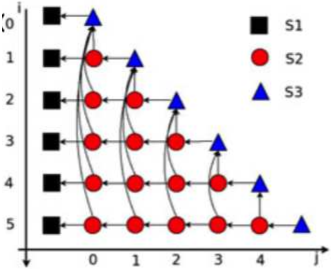
Dependence b/w S1 & S3

Ex: S1(2) ← S3(2)

- Polyhedral analyzers capture the above dependences into system of equalities and inequalities.

Polyhedral Compilation Techniques - Summary

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

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

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



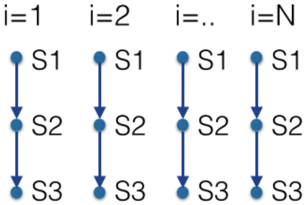
- Advantages
  - Precise data dependency computation
  - Unified formulation of complex set of loop transformations
- Limitations
  - Affine array subscripts, static affine control flow
  - But, conservative approaches exist !

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

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

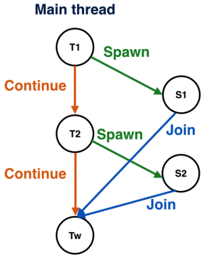


Explicit Parallelism

- 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'

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

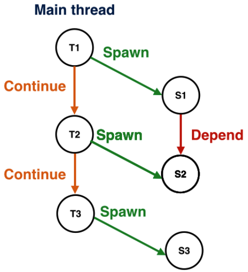


Explicit Parallelism

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

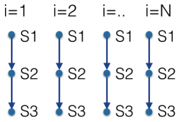
- Task-level parallelism with dependency (OpenMP 4.0)
  - Region of code is annotated with 'omp task depend'
  - Synchronization among **previously created** sibling tasks is achieved by 'depend' clauses

```
T1: #pragma omp task depend↩
    (out: A) {S1}
T2: #pragma omp task depend↩
    (in: A) {S2}
T3: #pragma omp task depend↩
    (out: B) {S3}
```

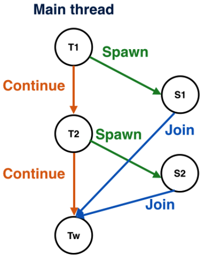


Explicit Parallelism

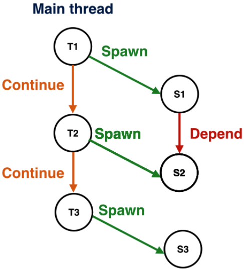
- Happens-Before relations
  - Specification of partial order
  - HB(S1, S2) $=$ *true* $\leftrightarrow$ S1 must happen before S2



HB(S1 (i), S2(i)) = true



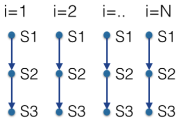
HB(S1, S2) = false



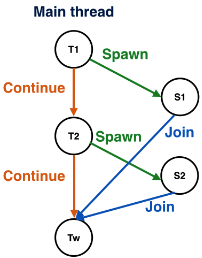
HB(S1, S2) = true

Explicit Parallelism

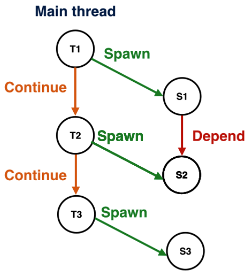
- Serial-Elision property
  - Removal of all parallel constructs results in a sequential program that is a valid (albeit inefficient) implementation of the parallel program semantics.



Satisfies



Satisfies



Satisfies

Explicit Parallelism

- Serial-Elision property
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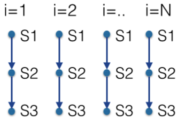
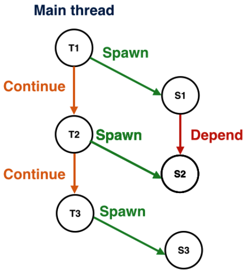
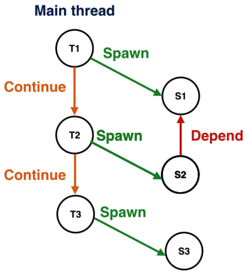


Satisfies



Satisfies



Not Satisfies (Not possible through depend clause)

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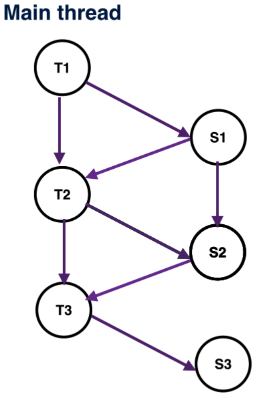
PoPP - Program Analysis

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

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

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



Conservative dependences

PoPP - Program Analysis

- Step1: Overestimate dependences based on the sequential order (Ignore parallel constructs)
- Step2: Compute HB relations

```
T1: #pragma omp task depend(out: A)
    { S1: E[F[..]] =  ..}
T2: #pragma omp task depend(in: A)
    { S2: G[E[..]] =  ..}
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```
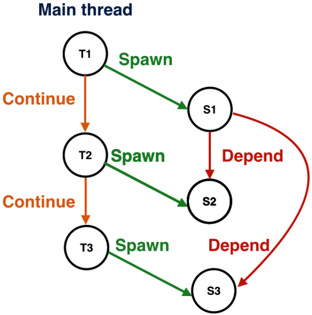
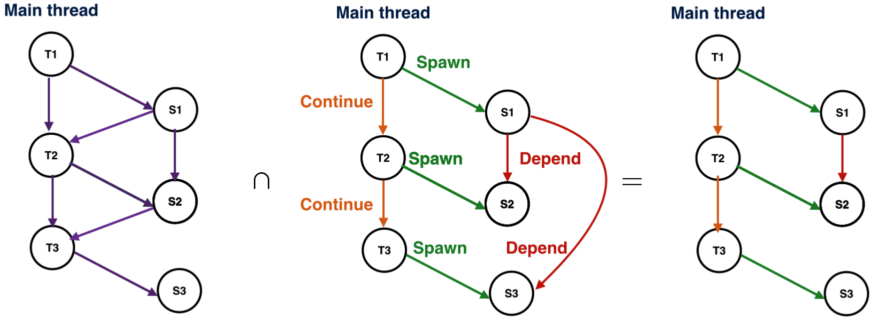



HB Relations

PoPP - Program Analysis

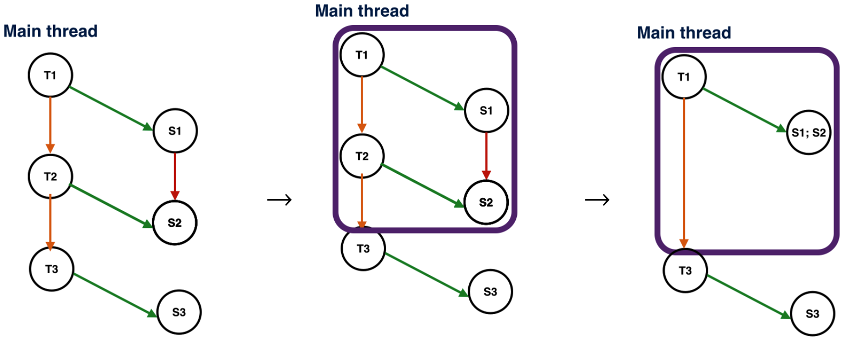
- Step1: Overestimate dependences based on the sequential order (Ignore parallel constructs)
- Step2: Compute HB relations
- Step3: Intersect 1 & 2 (Gives best of both worlds)



Conservative dependences HB Relations Refined dependences

PoPP - Program Transformations

- Step4: Use refined dependences to existing optimizers



Refined dependences

Fusion of S1 & S2 for better data locality

Optimized code

PoPP - Strategy

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, $\mathcal{S}$ = Transform($\mathcal{I}$, $\mathcal{P}'$)
6: $\mathcal{I}'$ = 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

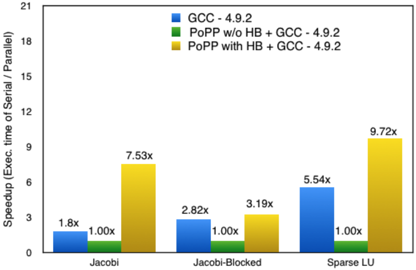
	Intel Xeon 5660 (Westmere)	**IBM Power 8E (Power 8)**
Microarch	Westmere	Power PC
Clock speed	2.80GHz	3.02GHz
Cores/socket	6	12
Total cores	12	24
Compiler	gcc/g++ -4.9.2 icc/icpc -14.0	gcc/g++ -4.9.2
Compiler flags	-O3 -fast(icc)	-O3

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



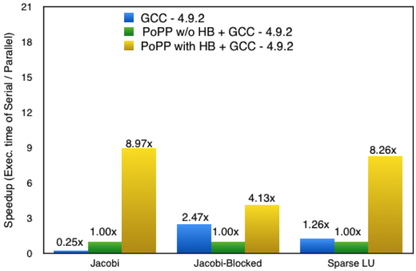
Jacobi: F, S, T, D
Jacobi-blocked: F, S, D
Sparse LU: F, D

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



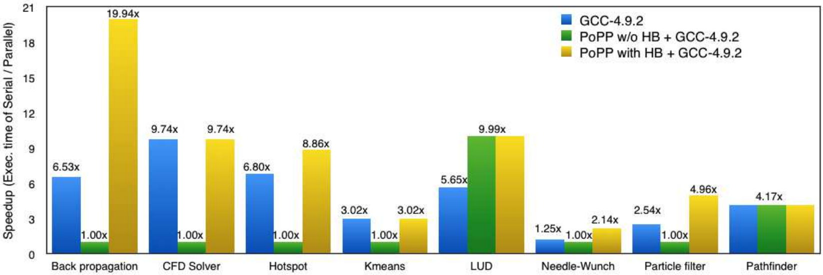
Jacobi: F, S, T, D
Jacobi-blocked: F, S, D
Sparse LU: F, D

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

- PoPP improved performance from 4.13X to 8.97X

PoPP performance on RODINIA Benchmarks - Intel

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

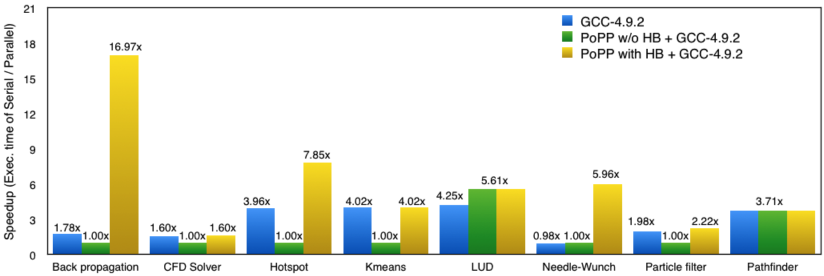


Intel Westmere with 12 cores

- 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

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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

Related work

- 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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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

- Acknowledgments
  - Rice Habanero Extreme Scale Software Research Group
  - PACT 2015 program committee