Combining Polyhedral and AST Transformations in CHiLL

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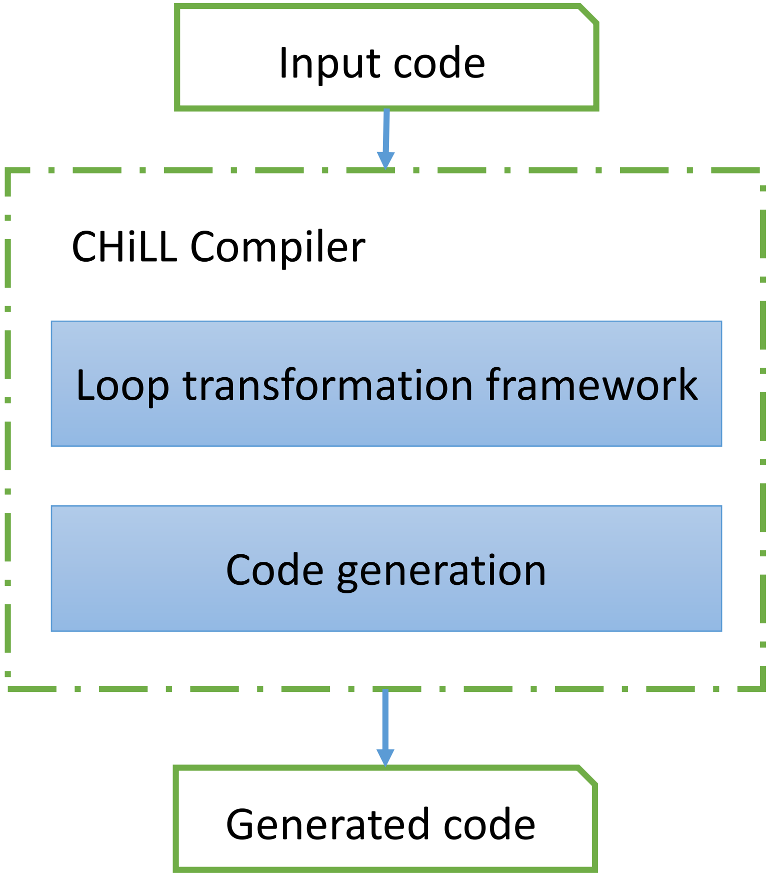
Outline

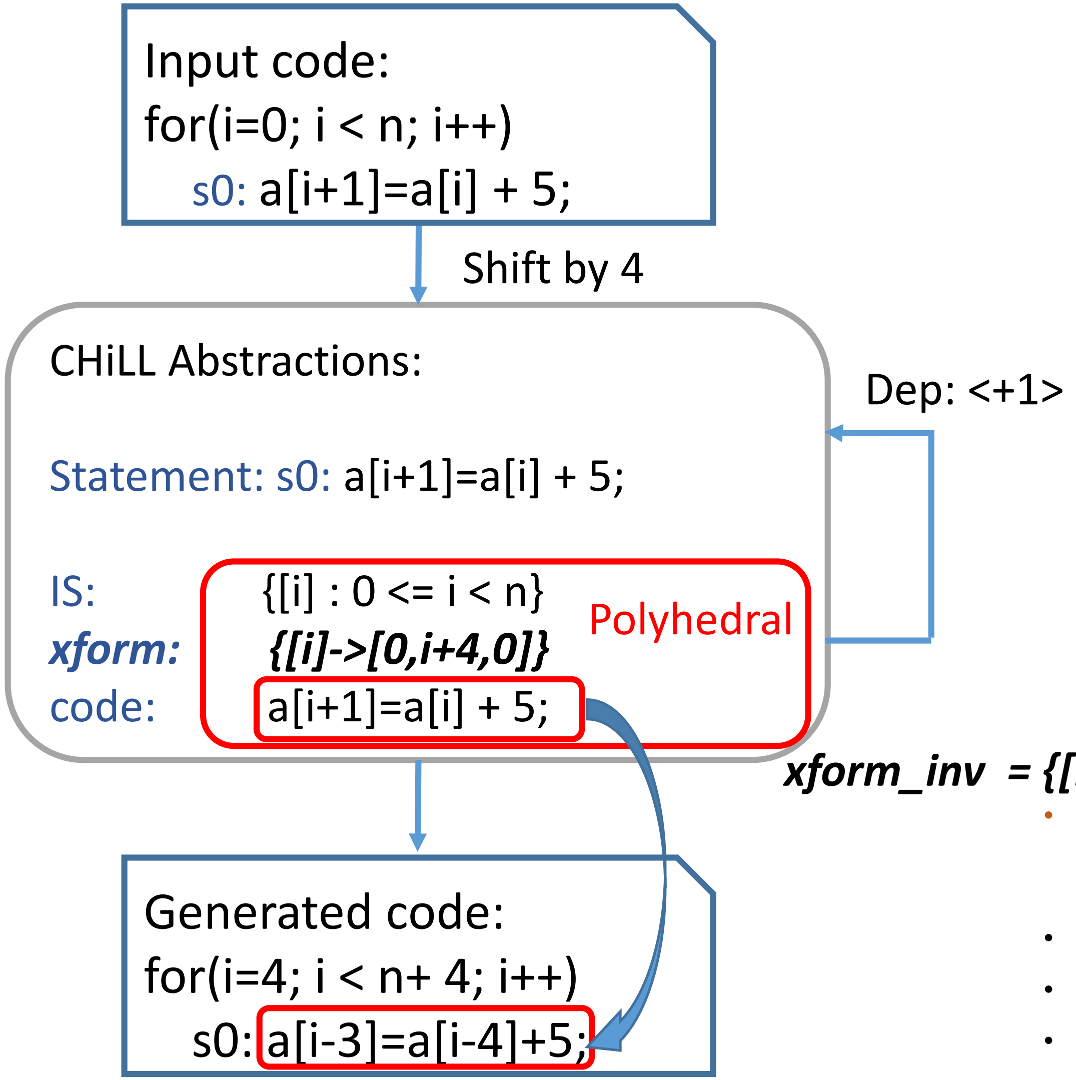
- Introduction
  - Problem
    - Limitations of polyhedral transformation
  - CHiLL Compiler Abstractions
    - Combining polyhedral and AST transformations
- Case Studies
  - Inspector/executor transformation for sparse matrix computation
  - Partial sum transformation for stencil optimization
  - Parallel code generation
    - CUDA
    - OpenMP
- Related Work
- Conclusion

Introduction

- Limitation of typical polyhedral transformation
  - Limited to affine domain
  - Transform iteration spaces
  - Array indices of statements updated
- Complicated optimizations
  - AST transformation as a post-pass outside of polyhedral framework
- Challenges
  - Leverage the power of composability of polyhedral framework

CHiLL Compiler Abstractions





Statement remains unmodified, other than array indices update

xform_inv = {[i]->[i-4]}

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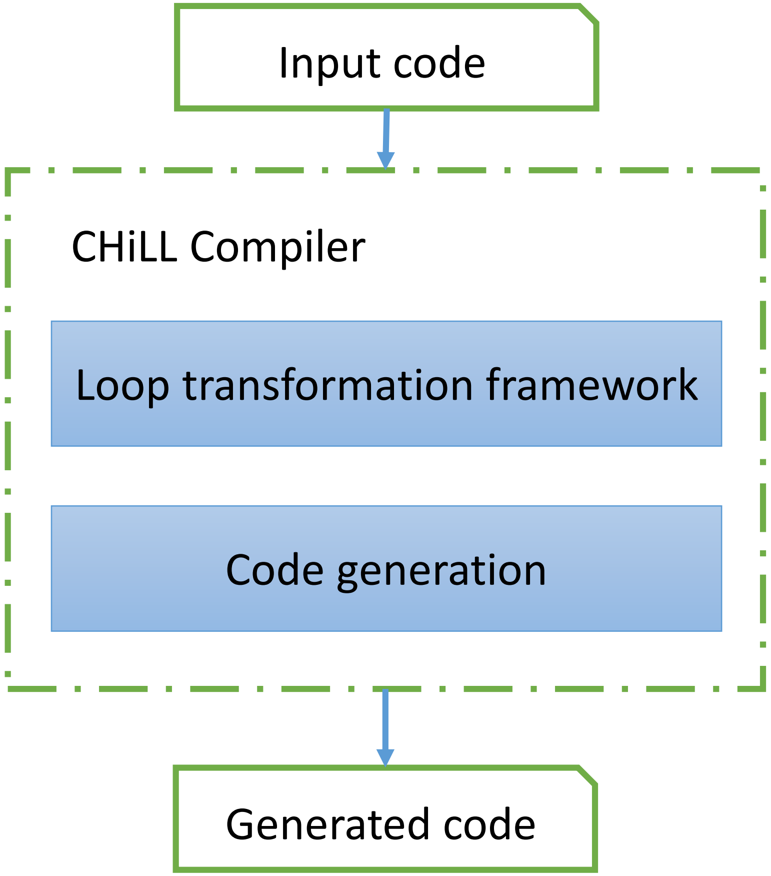
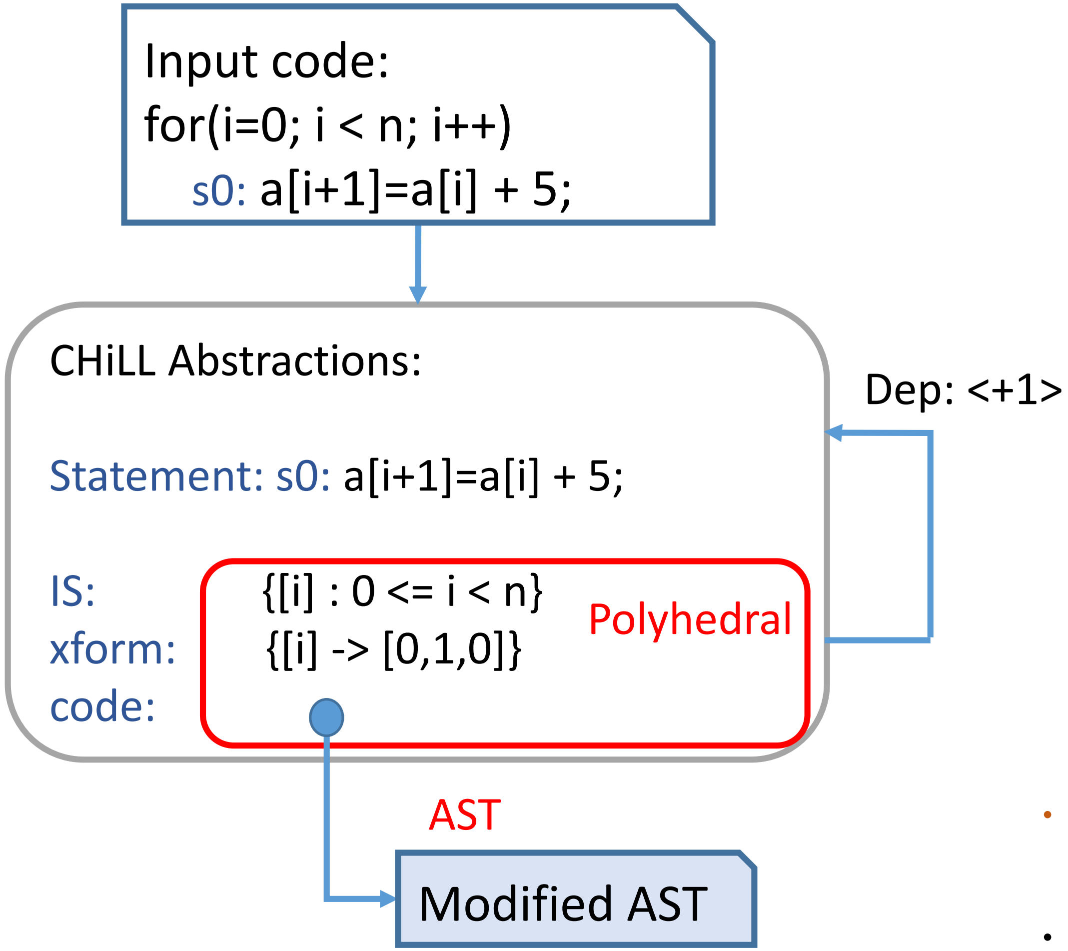
CHiLL Compiler Abstractions





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Non-Affine Extension – Coalesce Transformation

- Sparse matrix computation
  - Non-affine indirection through index arrays
    - Subscript expressions
      - x[col[j]]
    - Upper/lower loop bounds
      - index[i], index[i+1]
- Uninterpreted function symbol abstraction
  - Model functions or mappings (non-affine)
- Inspector/Executor mechanism
  - Inspector collects information at runtime used by optimized executor

CSR:
```
for(i=0; i < n; i++)
   for(j=index[i];j<index[i+1];j++)
      y[i]+=a[j]*x[col[j]]
```

Inspector Construction - Coalesce Transformation

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Input code:

```
for(i=0; i < n; i++)
   for(j=index[i];j<index[i+1];j++)
      y[i]+=a[j]*x[col[j]]
```

AST & Iteration Space Manipulation

$T_{coalesce} = \{[i,j] \rightarrow [k] \mid \mathbf{k=c(i,j)} \wedge 0 \leq k < NNZ\}$

```
struct c {
  int c_inv[][2];
  int k;
  void create_mapping(int i, int j) {
     c_inv[k][0] = i;
     c_inv[k][1] = j;
     k++;   }}
```

AST

Inspector code:

```
for(i = 0; i < n; i++)
  for(j = index[i]; j < index[i+1]; j++)
  code
```

```
c.create_mapping(i,j);
```

The input code's AST is modified to setup the data structures to represent the functionality of the inspector

Executor code:

```
for (k = 0; k < NNZ; k++)
code
```

Polyhedral

```
y[c_inv[k][0]] +=
  a[c_inv[k][1]]*x[col[c_inv[k][1]]];
```

Statement update

Composability preserved; Dependence graph incrementally updated

More Complicated I/E Transformations - BCSR

Input code:

```
for(i = 0; i < n; i++)
  for(j = index[i]; j < index[i+1]; j++)
    y[i] += a[j]*x[col[j]];
```

make-dense

```
for(i = 0; i < n; i++)
 for(k = 0; k < n; k++)
   for(j = index[i]; j < index[i+1]; j++)
     if(k == col[j])
       y[i]+=a[j]*x[k];
```

Tile(i,k)

```
for(ii=0;  ii < n/r; ii++)
 for(kk=0; kk < n/c; kk++)
  for(i=0; I < r; i++)
   for(k=0; k < c; k++)
    for(j=index[ii*r+i]; j < index[ii*r+i+1]; j++)
      if(kk*c+k == col[j])
        y[ii*r+i] += a[j]*x[kk*c+k];
```

Composable with other transformations

Compact-and-pad(kk,a,a')

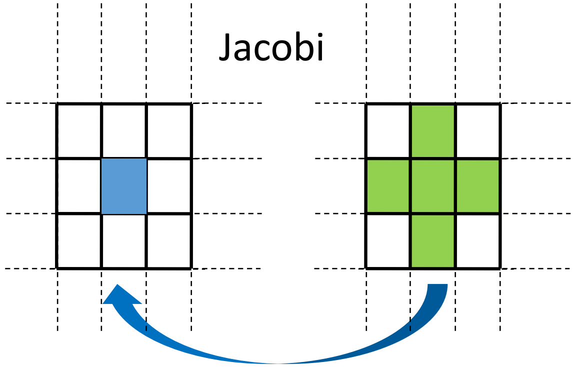
Inspector Code:

```
for(ii=0;  ii < n/r; ii++){
//reset marked to false (code not shown)
  for(i=0; i < r; i++)
    for(j=index[ii*r +i]; j < index[ii*r+i+1];j++) {
      code
}
```

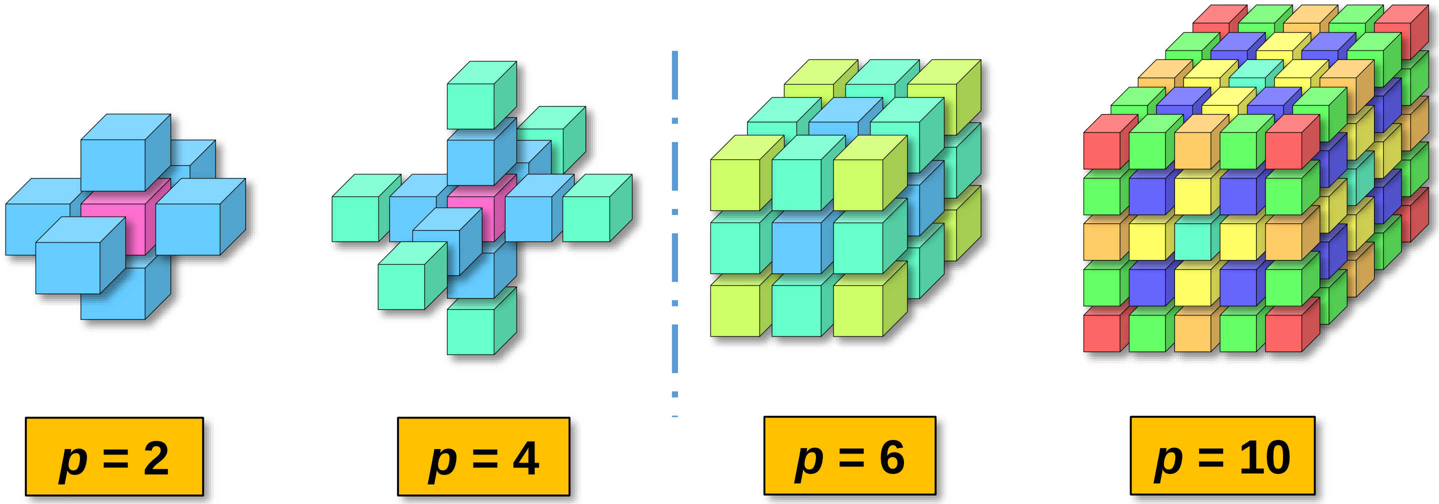
```
kk = col[j]/c; k=col[j]/c – kk*c;
      if(marked[kk] == false){
      marked[kk] = true;
      explicit_index[kk] = count;
      //initialize a'[count][0-r][0-c] to 0
      count++; }
      a'[count][i][k] = a[j]; }
      offset_index[ii+1] = count;
```

Partial Sum Transformation – Stencil Optimization

- Constant-coefficient Stencils
  - Weighted sum



- High-order Stencils



Partial Sum Transformation - Reuse

Still affine

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2D 9-point stencil

```
for (j=0; j<N; j++)
  for (i=0; i<N; i++) {
    out[j][i] =
          w1*( in[j-1][i] + in[j+1][i] +
                in[j][i-1] + in[j][i+1] ) +
          w2*( in[j-1][i-1] + in[j+1][i-1] +
                in[j-1][i+1] + in[j+1][i+1] ) +
          w3*( in[j][i] ); }
```

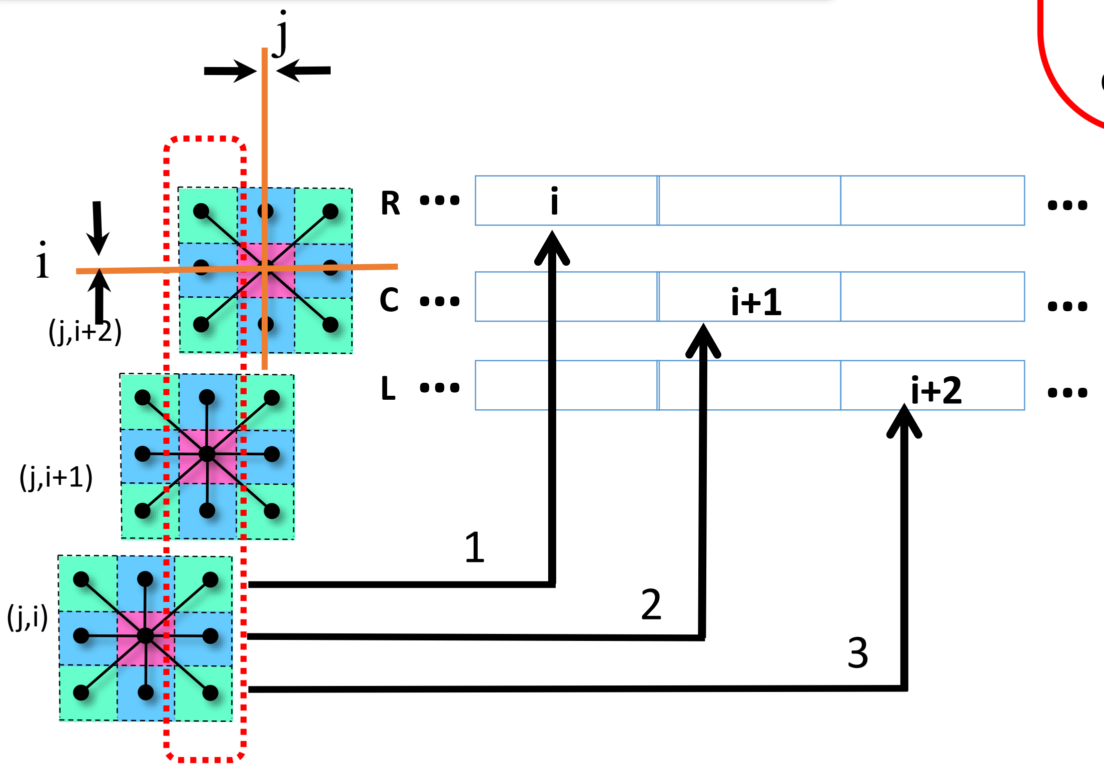
AST

```
r1 = in[j][i+1];
r2 = in[j+1][i+1] + in[j-1][i+1];

R[i]    = w1 * r1 + w2 * r2; ----- 1
C[i+1] = w3 * r1 + w1 * r2; ----- 2
L[i+2] = R[i]; ------------------- 3

out[j][i] = L[i] + C[i]+ R[i];
```

AST structure reparsed; Dependence graph rebuilt



- **Composable with communication-avoiding optimizations**
  - Overlapped tiling
  - Loop fusion
  - Wavefront

Parallel Code Generation

- Introduces
  - Parallel threads
  - Synchronization
  - Scaffolding code
- Approach
  - Apply transformations to set up for parallelization
    - E.g., tiling, datacopy
  - Annotate AST with aspects of parallel code generation
  - AST and polyhedral abstractions preserved until code generation, to facilitate composing transformations
  - Code generation emits specialized code

Parallel Code Generation - CUDA

```
void MM(int c[N][N], int a[N][N], int b[N][N]) {
for (i = 0; i < N; i++)
   for (j = 0; j < N; j++)
     for (k = 0; k < N; k++)
       c[j][i] = c[j][i] + a[k][i] * b[j][k]; }
```

```
tile_by_index(0,{"i","j"},{Ti,Tj},
{l1_control="ii",l2_control="jj"}, {"ii","jj","i","j","k"})
```

```
for(t2 = 0; t2 <= 7; t2++) // loop ii, block dimension x{
 for(t4 = 0; t4 <= 15; t4++) // loop jj, block dimension y{
  for(t6 = 128*t2; t6 <= 128*t2+127; t6++) // loop i {
   for(t8 = 64*t4; t8 <= 64*t4+63; t8++) // loop j {
    for(t10 = 0; t10 <= 1023; t10++) // loop k {
      s0(t2,t4,t6,t8,t10); }}}}}
```

```
cudaize(0,"mm_GPU",{}, {block={"ii","jj"},thread={"i","j"}},{})
```

- Impact to AST
  - AST annotation of block/thread loops
  - Loops are marked for elimination
  - Polyhedral and AST abstractions remain until code generation

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Parallel Code Generation - CUDA

```
void MM(int c[N][N], int a[N][N], int b[N][N]) {
for (i = 0; i < N; i++)
   for (j = 0; j < N; j++)
     for (k = 0; k < N; k++)
        c[j][i] = c[j][i] + a[k][i] * b[j][k]; }
```

```
tile_by_index(0,{"i","j"},{Ti,Tj},
{l1_control="ii",l2_control="jj"}, {"ii","jj","i","j","k"})
```

```
for(t2 = 0; t2 <= 7; t2++) // loop ii, block dimension x{
 for(t4 = 0; t4 <= 15; t4++) // loop jj, block dimension y{
  for(t6 = 128*t2; t6 <= 128*t2+127; t6++) // loop i {
   for(t8 = 64*t4; t8 <= 64*t4+63; t8++) // loop j {
    for(t10 = 0; t10 <= 1023; t10++) // loop k {
      s0(t2,t4,t6,t8,t10); }}}}}      blockIdx.x, blockIdx.y
```

```
cudaize(0,"mm_GPU",{}, {block={"ii","jj"},thread={"i","j"}},{})
```

- Impact to AST
  - AST annotation of block/thread loops
  - Loops are mark for elimination
  - Polyhedral and AST abstractions remain until code generation
  - Loop iterators are replaced with block/thread index
    - Eg, ii, jj replaced with blockIdx.x, blockIdx.y

Parallel Code Generation - CUDA

```
for (kk = 0; kk <= 63; kk += 1)
  for (iii = 0; iii <= 7; iii += 1)
    for (jjj = 0; jjj <= 3; jjj += 1)
      for (k = 16 * kk; k <= 16 * kk + 15; k += 1)
        c[...][...] = c[...][...] + a[...][...] * b[...][...];
```

copy_to_shared(0,"tx","a",-16)

```
for (kk = 0; kk <= 63; kk += 1) {
  for (tmp_tx = 0; tmp_tx <= 7; tmp_tx += 1)
    _P1[...][...] = a[...][...];
  __syncthreads();
  for (iii = 0; iii <= 7; iii += 1)
    for (jjj = 0; jjj <= 3; jjj += 1)
      for (k = 16 * kk; k <= 16 * kk + 15; k += 1)
        c[...][...] = c[...][...] + _P1[...][...] * b[...][...];
  __syncthreads(); }
```

AST

Kernel inlining

```
...
mm_GPU <<<dimGrid0 ,dimBlock0 >>>(...);
...
__global__ void mm_GPU(...)
{ ... }
```

AST

- Data Copy Transformation
- Synchronization
  - AST annotation
- Scaffolding code

Parallel Code Generation - OpenMP

```
#pragma omp parallel private (...) num_threads(6) {
  tid=omp_get_thread_num();
  for (k=-3; k<=66; k++) {
   loop jj      Strip mine the j loop: tile control loop
   for (t=0; t<=min(3,intFloor(t+3,2)); t++) {
    for (j=6*tid -3; j<=min(6*tid+2,66); j++) {
     for (i=t-3+intMod(-k-color -j-(t-3) ,2); i<=-t +66;
        i+=2) {
       S0(t,k-t,j,i); /* Laplacian */
       S1(t,k-t,j,i); /* Helhmoltz */
       S2(t,k-t,j,i); /* GSRB */    }}}
   //Explicit Spin Lock
   zplanes[tid] = t2;
   if (left != tid)
   {while(zplanes[left] < t2)
   { _mm_pause();}} else{}
   if (right != tid)
   {while(zplanes[right] < t2)
   {_mm_pause();}} }//end k }
```

point-to-point synchronization

- AST Manipulation
  - Tile, then control loop marked for elimination
  - Loop bound and statements update
  - OpenMP directives
  - Additional code
    - Synchronization and thread index

```
for (k=-3; k<=66; k++)
 for (t=0; t<=min(3,intFloor(t+3,2)); t++) {
  for (j=t-3; j<=-t+66; j++)
   for (i=t-3+intMod(-k-color -j-(t-3) ,2); i<=t+66; i+=2)
   {
     S0(t,k-t,j,i); /* Laplacian */
     S1(t,k-t,j,i); /* Helhmoltz */
     S2(t,k-t,j,i); /* GSRB */ }}
```

Related Work

- *J. Shirako* SC'14: ***Oil and water can mix: An integration of polyhedral and ast-based transformations***
  - Decoupled framework
  - Need to extract dependence information between stages
  - Polyhedral stage limited to affine domain

- *T. Grosser* TOPLAS'15: ***Polyhedral ast generation is more than scanning polyhedra***
  - User supplied AST expressions
  - Elegant for CUDA code generation
  - Expressing more complicated optimizations and data structures such as I/E transformation ?

Conclusion

- A broader class of optimizations supported by combining polyhedral and AST transformations

Optimization techniques	AST transformations	Polyhedral transformations	Composable with other optimizations
Inspector/executor for sparse codes	• Linked list struct in AST • Parse if condition in AST and convert to relation	• Encode sparse iteration space of executor • Derive closed form	• Datacopy, scalar expansion • Tiling and unrolling
Partial sums for high-order stencils	• Create partial sum buffers • Create new statements • Delete existing statements	• Create iteration spaces • Lexicographical ordering • New dependence graph	• Fusion, distribution • Skewing • Permutation
Parallel code generation	• Eliminate certain loops • Update statements • Synchronizations • Kernel launch/OMP clause	-----	-----