Workshop on Essential Abstractions in GCC

Parallelization and Vectorization in GCC

GCC Resource Center

(www.cse.iitb.ac.in/grc)

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3 July 2011

Outline

- An Overview of Loop Transformations in GCC
- Parallelization and Vectorization based on Lambda Framework
- Loop Transformations in Polytope Model
- Conclusions

Part 1

Parallelization and Vectorization in GCC using Lambda Framework

Loop Transforms in GCC

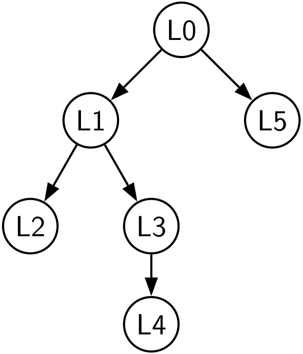
Implementation Issues

- Getting loop information (Loop discovery)
- Finding value spaces of induction variables, array subscript functions, and pointer accesses
- Analyzing data dependence
- Performing linear transformations

Loop Information

```
Loop0
{   Loop1
    {   Loop2
        {
        }
        Loop3
        {  Loop4
           {
           }
        }
    }
    Loop5
    {
    }
}
```

Loop Tree



Loop Transformation Passes in GCC

```
NEXT_PASS (pass_tree_loop);
  {
     struct opt_pass **p = &pass_tree_loop.pass.sub;
     NEXT_PASS (pass_tree_loop_init);
     NEXT_PASS (pass_lim);
     ...
     NEXT_PASS (pass_check_data_deps);
     NEXT_PASS (pass_loop_distribution);
     NEXT_PASS (pass_copy_prop);
     NEXT_PASS (pass_graphite);
       {
          struct opt_pass **p = &pass_graphite.pass.sub;
          NEXT_PASS (pass_graphite_transforms);
          ...
       }
     NEXT_PASS (pass_iv_canon);
     NEXT_PASS (pass_if_conversion);
     NEXT_PASS (pass_vectorize);
       {
          struct opt_pass **p = &pass_vectorize.pass.sub;
          NEXT_PASS (pass_lower_vector_ssa);
          NEXT_PASS (pass_dce_loop);
       }
     NEXT_PASS (pass_predcom);
     NEXT_PASS (pass_complete_unroll);
     NEXT_PASS (pass_slp_vectorize);
     NEXT_PASS (pass_parallelize_loops);
     NEXT_PASS (pass_loop_prefetch);
     NEXT_PASS (pass_iv_optimize);
     NEXT_PASS (pass_tree_loop_done);
  }
```

- Passes on tree-SSA form
  A variant of Gimple IR
- Discover parallelism and transform IR
- Parameterized by some machine dependent features (Vectorization factor, alignment etc.)
- Mapping the transformed IR to machine instructions is achieved through machine descriptions

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- Passes on tree-SSA form
  A variant of Gimple IR
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Loop Transformation Passes in GCC: Our Focus

Data Dependence	Pass variable name	`pass_check_data_deps`
	Enabling switch	`-fcheck-data-deps`
	Dump switch	`-fdump-tree-ckdd`
	Dump file extension	`.ckdd`
Loop Distribution	Pass variable name	`pass_loop_distribution`
	Enabling switch	`-ftree-loop-distribution`
	Dump switch	`-fdump-tree-ldist`
	Dump file extension	`.ldist`
Vectorization	Pass variable name	`pass_vectorize`
	Enabling switch	`-ftree-vectorize`
	Dump switch	`-fdump-tree-vect`
	Dump file extension	`.vect`
Parallelization	Pass variable name	`pass_parallelize_loops`
	Enabling switch	`-ftree-parallelize-loops=n`
	Dump switch	`-fdump-tree-parloops`
	Dump file extension	`.parloops`

Compiling for Emitting Dumps

- Other necessary command line switches
  - `-O3 -fdump-tree-all`
    `-O3` enables `-ftree-vectorize`. Other flags must be enabled explicitly
- Processor related switches to enable transformations apart from analysis
  - `-mtune=pentium -msse4`
- Other useful options
  - Suffixing `-all` to all dump switches
  - `-S` to stop the compilation with assembly generation
  - `--verbose-asm` to see more detailed assembly dump

Representing Value Spaces of Variables and Expressions

Chain of Recurrences: 3-tuple $\langle$Starting Value, modification, stride$\rangle$

```
for (i=3; i<=15; i=i+3)
{
    for (j=11; j>=1; j=j-2)
    {
        A[i+1][2*j-1] = ...
    }
}
```

Entity	CR
Induction variable `i`	$\{3, +, 3\}$
Induction variable `j`	$\{11, +, -2\}$
Index expression `i+1`	$\{4, +, 3\}$
Index expression `2*j-1`	$\{21, +, -4\}$

Advantages of Chain of Recurrences

CR can represent any affine expression

⇒ Accesses through pointers can also be tracked

```
int A[256], B[256];
int i, *p;
p = B;
for(i=1; i<200; i++)
{
  *(p++) = A[i] + *p;
  A[i] = *p;
}
```

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int A[256], B[256];
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{&B,+,4bytes}

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```

{&B,+,4bytes}

{&B+4bytes,+,4bytes}

Example 1: Observing Data Dependence

Step 0: Compiling

```
int a[200];
int main()
{
   int i;
   for (i=0; i<150; i++)
   {
      a[i] = a[i+1] + 2;
   }
   return 0;
}
```

```
gcc -fcheck-data-deps -fdump-tree-ckdd-all -O3 -S datadep.c
```

Example 1: Observing Data Dependence

Step 1: Examining the control flow graph

Program

```
int a[200];
int main()
{
   int i;
   for (i=0; i<150; i++)
   {
      a[i] = a[i+1] + 2;
   }
   return 0;
}
```

Control Flow Graph

```
<bb 3>:
  # i_13 = PHI <i_3(4), 0(2)>
  i_3 = i_13 + 1;
  D.1955_4 = a[i_3];
  D.1956_5 = D.1955_4 + 2;
  a[i_13] = D.1956_5;
  if (i_3 != 150)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Example 1: Observing Data Dependence

Step 1: Examining the control flow graph

Program	Control Flow Graph

<pre>int a[200];
int main()
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    int i;
    for (i=0; i<150; i++)
    {
        a[i] = a[i+1] + 2;
    }
    return 0;
}</pre>
	<pre><bb 3>:
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        a[i] = a[i+1] + 2;
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```

Control Flow Graph

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<bb 3>:
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Step 1: Examining the control flow graph

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   }
   return 0;
}</pre>
	<pre><bb 3>:
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Example 1: Observing Data Dependence

Step 2: Understanding the chain of recurrences

```
<bb 3>:
  # i_13 = PHI <i_3(4), 0(2)>
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```
(scalar_evolution = {0, +, 1}_1)
```

Example 1: Observing Data Dependence

Step 2: Understanding the chain of recurrences

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<bb 3>:
  # i_13 = PHI <i_3(4), 0(2)>
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  D.1956_5 = D.1955_4 + 2;
  a[i_13] = D.1956_5;
  if (i_3 != 150)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

```
(scalar_evolution = {1, +, 1}_1)
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Example 1: Observing Data Dependence

Step 2: Understanding the chain of recurrences

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  if (i_3 != 150)
    goto <bb 4>;
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    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

```
base_address: &a
offset from base address: 0
constant offset from base
                 address: 4
aligned to: 128
(chrec = {1, +, 1}_1)
```

Example 1: Observing Data Dependence

Step 2: Understanding the chain of recurrences

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  D.1956_5 = D.1955_4 + 2;
  a[i_13] = D.1956_5;
  if (i_3 != 150)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

```
base_address: &a
offset from base address: 0
constant offset from base
                 address:  0
aligned to: 128
base_object: a[0]
(chrec = {0, +, 1}_1)
```

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View	CFG View
• Relevant assignment is `a[i]` $=$ `a[i+1]` $+ 2$	

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

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• Relevant assignment is `a[i]` $=$ `a[i+1]` $+ 2$ • Solve for $0 \leq x, y < 150$ $$y = x + 1$$	

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View	CFG View
• Relevant assignment is `a[i]` $=$ `a[i+1]` $+ 2$ • Solve for $0 \leq x, y < 150$ $y = x + 1$ $\Rightarrow x - y + 1 = 0$	

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View	CFG View

- Relevant assignment is
  `a[i]` $=$ `a[i+1]` $+ 2$
- Solve for $0 \leq x, y < 150$

$$\begin{aligned} y &= x + 1 \\ \Rightarrow \quad x - y + 1 &= 0 \end{aligned}$$

- Find min and max of LHS

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

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$$\boxed{x - y + 1}$$

Min: -148 Max: +150

Example 1: Observing Data Dependence

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Min: -148 Max: $+150$

RHS belongs to $[-148, +150]$
and dependence may exist

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View

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  `a[i]` $=$ `a[i+1]` $+ 2$
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Min: -148 Max: $+150$

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CFG View

- ```
  i_3 = i_13 + 1;
  D.1955_4 = a[i_3];
  D.1956_5 = D.1955_4 + 2;
  a[i_13] = D.1956_5;
  ```
  ```

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View

- Relevant assignment is
  a[i] = a[i+1] + 2
- Solve for $0 \leq x, y < 150$

$$\begin{aligned} y &= x + 1 \\ \Rightarrow \quad x - y + 1 &= 0 \end{aligned}$$

- Find min and max of LHS

$$\boxed{x - y + 1}$$

Min: -148 Max: +150

RHS belongs to $[-148, +150]$
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CFG View

- ```
  i_3 = i_13 + 1;
  D.1955_4 = a[i_3];
  D.1956_5 = D.1955_4 + 2;
  a[i_13] = D.1956_5;
  ```
- Chain of recurrences are
  For a[i_3]: {1, +, 1}_1
  For a[i_13]: {0, +, 1}_1
  ```

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View

- Relevant assignment is

  a[i] $=$ a[i+1] $+ 2$

- Solve for $0 \leq x, y < 150$

$$\begin{aligned} y &= x + 1 \\ \Rightarrow \quad x - y + 1 &= 0 \end{aligned}$$

- Find min and max of LHS

$$\boxed{x - y + 1}$$

Min: -148 Max: $+150$

RHS belongs to $[-148, +150]$ and dependence may exist

CFG View

- ```
  i_3 = i_13 + 1;
  D.1955_4 = a[i_3];
  D.1956_5 = D.1955_4 + 2;
  a[i_13] = D.1956_5;
  ```

- Chain of recurrences are

  For `a[i_3]`: `{1, +, 1}_1`

  For `a[i_13]`: `{0, +, 1}_1`

- Solve for $0 \leq$ `x_1` < 150

  `1 + 1*x_1` $-$ `0 + 1*x_1` $= 0$
  ```

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View

- Relevant assignment is
  a[i] = a[i+1] + 2
- Solve for $0 \leq x, y < 150$

$$\begin{aligned} y &= x + 1 \\ \Rightarrow \quad x - y + 1 &= 0 \end{aligned}$$

- Find min and max of LHS

$$\boxed{x - y + 1}$$

Min: -148 Max: +150

RHS belongs to $[-148, +150]$ and dependence may exist

CFG View

- ```
  i_3 = i_13 + 1;
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  ```
- Chain of recurrences are
  For `a[i_3]`: `{1, +, 1}_1`
  For `a[i_13]`: `{0, +, 1}_1`
- Solve for $0 \leq$ `x_1` < 150
  `1 + 1*x_1` $-$ `0 + 1*x_1` $= 0$
- Min of LHS is -148, Max is +150
  ```

Example 1: Observing Data Dependence

Step 3: Understanding Banerjee's test

Source View

- Relevant assignment is
  a[i] $=$ a[i+1] $+ 2$
- Solve for $0 \le x, y < 150$

$$\begin{aligned} y &= x + 1 \\ \Rightarrow \quad x - y + 1 &= 0 \end{aligned}$$

- Find min and max of LHS

$$\boxed{x - y + 1}$$

Min: -148 Max: $+150$

RHS belongs to $[-148, +150]$
and dependence may exist

CFG View

- ```
  i_3 = i_13 + 1;
  D.1955_4 = a[i_3];
  D.1956_5 = D.1955_4 + 2;
  a[i_13] = D.1956_5;
  ```
- Chain of recurrences are
  For a[i_3]: {1, +, 1}_1
  For a[i_13]: {0, +, 1}_1
- Solve for $0 \le$ x_1 < 150
  1 + 1*x_1 $-$ 0 + 1*x_1 $= 0$
- Min of LHS is -148, Max is $+150$
- Dependence may exist
  ```

Example 1: Observing Data Dependence

Step 4: Observing the data dependence information

```
iterations_that_access_an_element_twice_in_A: [1 + 1 * x_1]
last_conflict: 149
iterations_that_access_an_element_twice_in_B: [0 + 1 * x_1]
last_conflict: 149
Subscript distance: 1
```

```
inner loop index: 0
loop nest: (1)
distance_vector: 1
direction_vector: +
```

Example 2: Observing Vectorization and Parallelization

Step 0: Compiling the code with `-O3`

```
int a[256], b[256];
int main()
{
    int i;
    for (i=0; i<256; i++)
    {
        a[i] = b[i];
    }
    return 0;
}
```

- Additional options for parallelization
  `-ftree-parallelize-loops=2 -fdump-tree-parloops-all`
- Additional options for vectorization
  `-fdump-tree-vect-all -msse4`

Example 2: Observing Vectorization and Parallelization

Step 1: Examining the control flow graph

Program

```
int a[256], b[256];
int main()
{
    int i;
    for (i=0; i<256; i++)
    {
        a[i] = b[i];
    }
    return 0;
}
```

Control Flow Graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.2836_3 = b[i_11];
  a[i_11] = D.2836_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Example 2: Observing Vectorization and Parallelization

Step 1: Examining the control flow graph

Program

```
int a[256], b[256];
int main()
{
    int i;
    for (i=0; i<256; i++)
    {
        a[i] = b[i];
    }
    return 0;
}
```

Control Flow Graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.2836_3 = b[i_11];
  a[i_11] = D.2836_3;
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    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Example 2: Observing Vectorization and Parallelization

Step 1: Examining the control flow graph

Program	Control Flow Graph

<pre>int a[256], b[256];
int main()
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        a[i] = b[i];
    }
    return 0;
}</pre>
	<pre><bb 3>:
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	  D.2836_3 = b[i_11];
	  a[i_11] = D.2836_3;
	  i_4 = i_11 + 1;
	  if (i_4 != 256)
	    goto <bb 4>;
	  else
	    goto <bb 5>;
	<bb 4>:
	  goto <bb 3>;</pre>

Example 2: Observing Vectorization and Parallelization

Step 2: Observing the final decision about vectorization

```
parvec.c:5: note: LOOP VECTORIZED.
parvec.c:2: note: vectorized 1 loops in function.
```

Example 2: Observing Vectorization and Parallelization

Step 3: Examining the vectorized control flow graph

Original control flow graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.2836_3 = b[i_11];
  a[i_11] = D.2836_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Transformed control flow graph

```
<bb 2>:
  vect_pb.7_10 = &b;
  vect_pa.12_15 = &a;
<bb 3>:
  # vect_pb.4_6 = PHI <vect_pb.4_13,
                        vect_pb.7_10>
  # vect_pa.9_16 = PHI <vect_pa.9_17,
                        vect_pa.12_15>
  vect_var_.8_14 = MEM[vect_pb.4_6];
  MEM[vect_pa.9_16] = vect_var_.8_14;
  vect_pb.4_13 = vect_pb.4_6 + 16;
  vect_pa.9_17 = vect_pa.9_16 + 16;
  ivtmp.13_19 = ivtmp.13_18 + 1;
  if (ivtmp.13_19 < 64)
    goto <bb 4>;
```

Example 2: Observing Vectorization and Parallelization

Step 3: Examining the vectorized control flow graph

Original control flow graph	Transformed control flow graph

<pre><bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.2836_3 = b[i_11];
  a[i_11] = D.2836_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;</pre>
	<pre><bb 2>:
	  vect_pb.7_10 = &b;
	  vect_pa.12_15 = &a;
	<bb 3>:
	  # vect_pb.4_6 = PHI <vect_pb.4_13,
	                    vect_pb.7_10>
	  # vect_pa.9_16 = PHI <vect_pa.9_17,
	                    vect_pa.12_15>
	  vect_var_.8_14 = MEM[vect_pb.4_6];
	  MEM[vect_pa.9_16] = vect_var_.8_14;
	  vect_pb.4_13 = vect_pb.4_6 + 16;
	  vect_pa.9_17 = vect_pa.9_16 + 16;
	  ivtmp.13_19 = ivtmp.13_18 + 1;
	  if (ivtmp.13_19 < 64)
	    goto <bb 4>;</pre>

Example 2: Observing Vectorization and Parallelization

Step 3: Examining the vectorized control flow graph

Original control flow graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.2836_3 = b[i_11];
  a[i_11] = D.2836_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Transformed control flow graph

```
<bb 2>:
  vect_pb.7_10 = &b;
  vect_pa.12_15 = &a;
<bb 3>:
  # vect_pb.4_6 = PHI <vect_pb.4_13,
                  vect_pb.7_10>
  # vect_pa.9_16 = PHI <vect_pa.9_17,
                  vect_pa.12_15>
  vect_var_.8_14 = MEM[vect_pb.4_6];
  MEM[vect_pa.9_16] = vect_var_.8_14;
  vect_pb.4_13 = vect_pb.4_6 + 16;
  vect_pa.9_17 = vect_pa.9_16 + 16;
  ivtmp.13_19 = ivtmp.13_18 + 1;
  if (ivtmp.13_19 < 64)
    goto <bb 4>;
```

Example 2: Observing Vectorization and Parallelization

Step 3: Examining the vectorized control flow graph

Original control flow graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.2836_3 = b[i_11];
  a[i_11] = D.2836_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Transformed control flow graph

```
<bb 2>:
  vect_pb.7_10 = &b;
  vect_pa.12_15 = &a;
<bb 3>:
  # vect_pb.4_6 = PHI <vect_pb.4_13,
                       vect_pb.7_10>
  # vect_pa.9_16 = PHI <vect_pa.9_17,
                       vect_pa.12_15>
  vect_var_.8_14 = MEM[vect_pb.4_6];
  MEM[vect_pa.9_16] = vect_var_.8_14;
  vect_pb.4_13 = vect_pb.4_6 + 16;
  vect_pa.9_17 = vect_pa.9_16 + 16;
  ivtmp.13_19 = ivtmp.13_18 + 1;
  if (ivtmp.13_19 < 64)
    goto <bb 4>;
```

Example 2: Observing Vectorization and Parallelization

Step 3: Examining the vectorized control flow graph

Original control flow graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.2836_3 = b[i_11];
  a[i_11] = D.2836_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Transformed control flow graph

```
<bb 2>:
  vect_pb.7_10 = &b;
  vect_pa.12_15 = &a;
<bb 3>:
  # vect_pb.4_6 = PHI <vect_pb.4_13,
                       vect_pb.7_10>
  # vect_pa.9_16 = PHI <vect_pa.9_17,
                       vect_pa.12_15>
  vect_var_.8_14 = MEM[vect_pb.4_6];
  MEM[vect_pa.9_16] = vect_var_.8_14;
  vect_pb.4_13 = vect_pb.4_6 + 16;
  vect_pa.9_17 = vect_pa.9_16 + 16;
  ivtmp.13_19 = ivtmp.13_18 + 1;
  if (ivtmp.13_19 < 64)
    goto <bb 4>;
```

Example 2: Observing Vectorization and Parallelization

Step 4: Understanding the strategy of parallel execution

- Create threads t_i for $1 \leq i \leq$ MAX_THREADS

Example 2: Observing Vectorization and Parallelization

Step 4: Understanding the strategy of parallel execution

- Create threads t_i for $1 \leq i \leq$ MAX_THREADS
- Assigning start and end iteration for each thread
  $\Rightarrow$ Distribute iteration space across all threads

Example 2: Observing Vectorization and Parallelization

Step 4: Understanding the strategy of parallel execution

- Create threads t_i for $1 \leq i \leq$ MAX_THREADS
- Assigning start and end iteration for each thread
  $\Rightarrow$ Distribute iteration space across all threads
- Create the following code body for each thread t_i

```
for (j=start_for_thread_i; j<=end_for_thread_i; j++)
{
     /* execute the loop body to be parallelized */
}
```

Example 2: Observing Vectorization and Parallelization

Step 4: Understanding the strategy of parallel execution

- Create threads t_i for $1 \leq i \leq$ MAX_THREADS
- Assigning start and end iteration for each thread
  $\Rightarrow$ Distribute iteration space across all threads
- Create the following code body for each thread t_i

```
for (j=start_for_thread_i; j<=end_for_thread_i; j++)
{
     /* execute the loop body to be parallelized */
}
```

- All threads are executed in parallel

Example 2: Observing Vectorization and Parallelization

Step 5: Examining the thread creation in parallelized control flow graph

```
D.1996_6 = __builtin_omp_get_num_threads ();
D.1998_8 = __builtin_omp_get_thread_num ();
D.2000_10 = 255 / D.1997_6;
D.2001_11 = D.2000_10 * D.1997_6;
D.2002_12 = D.2001_11 != 255;
D.2003_13 = D.2002_12 + D.2000_10;
ivtmp.7_14 = D.2003_13 * D.1999_8;
D.2005_15 = ivtmp.7_14 + D.2003_13;
D.2006_16 = MIN_EXPR <D.2005_15, 255>;
if (ivtmp.7_14 >= D.2006_16)
  goto <bb 3>;
```

Example 2: Observing Vectorization and Parallelization

Step 5: Examining the thread creation in parallelized control flow graph

```
D.1996_6 = __builtin_omp_get_num_threads ();
D.1998_8 = __builtin_omp_get_thread_num ();
D.2000_10 = 255 / D.1997_6;
D.2001_11 = D.2000_10 * D.1997_6;
D.2002_12 = D.2001_11 != 255;
D.2003_13 = D.2002_12 + D.2000_10;
ivtmp.7_14 = D.2003_13 * D.1999_8;
D.2005_15 = ivtmp.7_14 + D.2003_13;
D.2006_16 = MIN_EXPR <D.2005_15, 255>;
if (ivtmp.7_14 >= D.2006_16)
  goto <bb 3>;
```

Get the number of threads

Example 2: Observing Vectorization and Parallelization

Step 5: Examining the thread creation in parallelized control flow graph

```
D.1996_6 = __builtin_omp_get_num_threads ();
D.1998_8 = __builtin_omp_get_thread_num ();
D.2000_10 = 255 / D.1997_6;
D.2001_11 = D.2000_10 * D.1997_6;
D.2002_12 = D.2001_11 != 255;
D.2003_13 = D.2002_12 + D.2000_10;
ivtmp.7_14 = D.2003_13 * D.1999_8;
D.2005_15 = ivtmp.7_14 + D.2003_13;
D.2006_16 = MIN_EXPR <D.2005_15, 255>;
if (ivtmp.7_14 >= D.2006_16)
  goto <bb 3>;
```

Get thread identity

Example 2: Observing Vectorization and Parallelization

Step 5: Examining the thread creation in parallelized control flow graph

```
D.1996_6 = __builtin_omp_get_num_threads ();
D.1998_8 = __builtin_omp_get_thread_num ();
D.2000_10 = 255 / D.1997_6;
D.2001_11 = D.2000_10 * D.1997_6;
D.2002_12 = D.2001_11 != 255;
D.2003_13 = D.2002_12 + D.2000_10;
ivtmp.7_14 = D.2003_13 * D.1999_8;
D.2005_15 = ivtmp.7_14 + D.2003_13;
D.2006_16 = MIN_EXPR <D.2005_15, 255>;
if (ivtmp.7_14 >= D.2006_16)
  goto <bb 3>;
```

Perform load calculations

Example 2: Observing Vectorization and Parallelization

Step 5: Examining the thread creation in parallelized control flow graph

```
D.1996_6 = __builtin_omp_get_num_threads ();
D.1998_8 = __builtin_omp_get_thread_num ();
D.2000_10 = 255 / D.1997_6;
D.2001_11 = D.2000_10 * D.1997_6;
D.2002_12 = D.2001_11 != 255;
D.2003_13 = D.2002_12 + D.2000_10;
ivtmp.7_14 = D.2003_13 * D.1999_8;
D.2005_15 = ivtmp.7_14 + D.2003_13;
D.2006_16 = MIN_EXPR <D.2005_15, 255>;
if (ivtmp.7_14 >= D.2006_16)
  goto <bb 3>;
```

Assign start iteration to the chosen thread

Example 2: Observing Vectorization and Parallelization

Step 5: Examining the thread creation in parallelized control flow graph

```
D.1996_6 = __builtin_omp_get_num_threads ();
D.1998_8 = __builtin_omp_get_thread_num ();
D.2000_10 = 255 / D.1997_6;
D.2001_11 = D.2000_10 * D.1997_6;
D.2002_12 = D.2001_11 != 255;
D.2003_13 = D.2002_12 + D.2000_10;
ivtmp.7_14 = D.2003_13 * D.1999_8;
D.2005_15 = ivtmp.7_14 + D.2003_13;
D.2006_16 = MIN_EXPR <D.2005_15, 255>;
if (ivtmp.7_14 >= D.2006_16)
  goto <bb 3>;
```

Assign end iteration to the chosen thread

Example 2: Observing Vectorization and Parallelization

Step 5: Examining the thread creation in parallelized control flow graph

```
D.1996_6 = __builtin_omp_get_num_threads ();
D.1998_8 = __builtin_omp_get_thread_num ();
D.2000_10 = 255 / D.1997_6;
D.2001_11 = D.2000_10 * D.1997_6;
D.2002_12 = D.2001_11 != 255;
D.2003_13 = D.2002_12 + D.2000_10;
ivtmp.7_14 = D.2003_13 * D.1999_8;
D.2005_15 = ivtmp.7_14 + D.2003_13;
D.2006_16 = MIN_EXPR <D.2005_15, 255>;
if (ivtmp.7_14 >= D.2006_16)
  goto <bb 3>;
```

Start execution of iterations of the chosen thread

Example 2: Observing Vectorization and Parallelization

Step 6: Examining the loop body to be executed by a thread

Control Flow Graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.1956_3 = b[i_11];
  a[i_11] = D.1956_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Parallel loop body

```
<bb 5>:
  i.8_21 = (int) ivtmp.7_18;
  D.2010_23 = *b.10_4[i.8_21];
  *a.11_5[i.8_21] = D.2010_23;
  ivtmp.7_19 = ivtmp.7_18 + 1;
  if (D.2006_16 > ivtmp.7_19)
    goto <bb 5>;
  else
    goto <bb 3>;
```

Example 2: Observing Vectorization and Parallelization

Step 6: Examining the loop body to be executed by a thread

Control Flow Graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.1956_3 = b[i_11];
  a[i_11] = D.1956_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Parallel loop body

```
<bb 5>:
  i.8_21 = (int) ivtmp.7_18;
  D.2010_23 = *b.10_4[i.8_21];
  *a.11_5[i.8_21] = D.2010_23;
  ivtmp.7_19 = ivtmp.7_18 + 1;
  if (D.2006_16 > ivtmp.7_19)
    goto <bb 5>;
  else
    goto <bb 3>;
```

Example 2: Observing Vectorization and Parallelization

Step 6: Examining the loop body to be executed by a thread

Control Flow Graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.1956_3 = b[i_11];
  a[i_11] = D.1956_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Parallel loop body

```
<bb 5>:
  i.8_21 = (int) ivtmp.7_18;
  D.2010_23 = *b.10_4[i.8_21];
  *a.11_5[i.8_21] = D.2010_23;
  ivtmp.7_19 = ivtmp.7_18 + 1;
  if (D.2006_16 > ivtmp.7_19)
    goto <bb 5>;
  else
    goto <bb 3>;
```

Example 2: Observing Vectorization and Parallelization

Step 6: Examining the loop body to be executed by a thread

Control Flow Graph	Parallel loop body

```<bb 3>:```
``` # i_11 = PHI <i_4(4), 0(2)>```
``` D.1956_3 = b[i_11];```
``` a[i_11] = D.1956_3;```
``` i_4 = i_11 + 1;```
``` if (i_4 != 256)```
```   goto <bb 4>;```
``` else```
```   goto <bb 5>;```
```<bb 4>:```
``` goto <bb 3>;```
	```<bb 5>:```
	``` i.8_21 = (int) ivtmp.7_18;```
	``` D.2010_23 = *b.10_4[i.8_21];```
	``` *a.11_5[i.8_21] = D.2010_23;```
	``` ivtmp.7_19 = ivtmp.7_18 + 1;```
	``` if (D.2006_16 > ivtmp.7_19)```
	``` goto <bb 5>;```
	``` else```
	``` goto <bb 3>;```

Example 2: Observing Vectorization and Parallelization

Step 6: Examining the loop body to be executed by a thread

Control Flow Graph

```
<bb 3>:
  # i_11 = PHI <i_4(4), 0(2)>
  D.1956_3 = b[i_11];
  a[i_11] = D.1956_3;
  i_4 = i_11 + 1;
  if (i_4 != 256)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Parallel loop body

```
<bb 5>:
  i.8_21 = (int) ivtmp.7_18;
  D.2010_23 = *b.10_4[i.8_21];
  *a.11_5[i.8_21] = D.2010_23;
  ivtmp.7_19 = ivtmp.7_18 + 1;
  if (D.2006_16 > ivtmp.7_19)
    goto <bb 5>;
  else
    goto <bb 3>;
```

Example 3: Vectorization but No Parallelization

Step 0: Compiling with

`-O3 -fdump-tree-vect-all -msse4`

```
int a[624];
int main()
{
    int i;
    for (i=0; i<619; i++)
    {
        a[i] = a[i+4];
    }
    return 0;
}
```

Example 3: Vectorization but No Parallelization

Step 1: Observing the final decision about vectorization

```
vecnopar.c:5: note: LOOP VECTORIZED.
vecnopar.c:2: note: vectorized 1 loops in function.
```

Example 3: Vectorization but No Parallelization

Step 2: Examining vectorization

Control Flow Graph

```
<bb 3>:
  # i_12 = PHI <i_5(4), 0(2)>
  D.2834_3 = i_12 + 4;
  D.2835_4 = a[D.2834_3];
  a[i_12] = D.2835_4;
  i_5 = i_12 + 1;
  if (i_5 != 619)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Vectorized Control Flow Graph

```
<bb 2>:
  vect_pa.10_26 = &a[4];
  vect_pa.15_30 = &a;
<bb 3>:
  # vect_pa.7_27 = PHI <vect_pa.7_28,
                        vect_pa.10_26>
  # vect_pa.12_31 = PHI <vect_pa.12_32,
                        vect_pa.15_30>
  vect_var_.11_29 = MEM[vect_pa.7_27];
  MEM[vect_pa.12_31] = vect_var_.11_29;
  vect_pa.7_28 = vect_pa.7_27 + 16;
  vect_pa.12_32 = vect_pa.12_31 + 16;
  ivtmp.16_34 = ivtmp.16_33 + 1;
  if (ivtmp.16_34 < 154)
    goto <bb 4>;
```

Example 3: Vectorization but No Parallelization

Step 2: Examining vectorization

Control Flow Graph

```
<bb 3>:
  # i_12 = PHI <i_5(4), 0(2)>
  D.2834_3 = i_12 + 4;
  D.2835_4 = a[D.2834_3];
  a[i_12] = D.2835_4;
  i_5 = i_12 + 1;
  if (i_5 != 619)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Vectorized Control Flow Graph

```
<bb 2>:
  vect_pa.10_26 = &a[4];
  vect_pa.15_30 = &a;
<bb 3>:
  # vect_pa.7_27 = PHI <vect_pa.7_28,
                        vect_pa.10_26>
  # vect_pa.12_31 = PHI <vect_pa.12_32,
                        vect_pa.15_30>
  vect_var_.11_29 = MEM[vect_pa.7_27];
  MEM[vect_pa.12_31] = vect_var_.11_29;
  vect_pa.7_28 = vect_pa.7_27 + 16;
  vect_pa.12_32 = vect_pa.12_31 + 16;
  ivtmp.16_34 = ivtmp.16_33 + 1;
  if (ivtmp.16_34 < 154)
    goto <bb 4>;
```

Example 3: Vectorization but No Parallelization

Step 2: Examining vectorization

Control Flow Graph

```
<bb 3>:
  # i_12 = PHI <i_5(4), 0(2)>
  D.2834_3 = i_12 + 4;
  D.2835_4 = a[D.2834_3];
  a[i_12] = D.2835_4;
  i_5 = i_12 + 1;
  if (i_5 != 619)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Vectorized Control Flow Graph

```
<bb 2>:
  vect_pa.10_26 = &a[4];
  vect_pa.15_30 = &a;
<bb 3>:
  # vect_pa.7_27 = PHI <vect_pa.7_28,
                        vect_pa.10_26>
  # vect_pa.12_31 = PHI <vect_pa.12_32,
                        vect_pa.15_30>
  vect_var_.11_29 = MEM[vect_pa.7_27];
  MEM[vect_pa.12_31] = vect_var_.11_29;
  vect_pa.7_28 = vect_pa.7_27 + 16;
  vect_pa.12_32 = vect_pa.12_31 + 16;
  ivtmp.16_34 = ivtmp.16_33 + 1;
  if (ivtmp.16_34 < 154)
    goto <bb 4>;
```

Example 3: Vectorization but No Parallelization

Step 2: Examining vectorization

Control Flow Graph	Vectorized Control Flow Graph

<pre><bb 3>:
  # i_12 = PHI <i_5(4), 0(2)>
  D.2834_3 = i_12 + 4;
  D.2835_4 = a[D.2834_3];
  a[i_12] = D.2835_4;
  i_5 = i_12 + 1;
  if (i_5 != 619)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;</pre>
	<pre><bb 2>:
	  vect_pa.10_26 = &a[4];
	  vect_pa.15_30 = &a;
	<bb 3>:
	  # vect_pa.7_27 = PHI <vect_pa.7_28,
	                        vect_pa.10_26>
	  # vect_pa.12_31 = PHI <vect_pa.12_32,
	                        vect_pa.15_30>
	  vect_var_.11_29 = MEM[vect_pa.7_27];
	  MEM[vect_pa.12_31] = vect_var_.11_29;
	  vect_pa.7_28 = vect_pa.7_27 + 16;
	  vect_pa.12_32 = vect_pa.12_31 + 16;
	  ivtmp.16_34 = ivtmp.16_33 + 1;
	  if (ivtmp.16_34 < 154)
	    goto <bb 4>;</pre>

Example 3: Vectorization but No Parallelization

Step 2: Examining vectorization

Control Flow Graph

```
<bb 3>:
  # i_12 = PHI <i_5(4), 0(2)>
  D.2834_3 = i_12 + 4;
  D.2835_4 = a[D.2834_3];
  a[i_12] = D.2835_4;
  i_5 = i_12 + 1;
  if (i_5 != 619)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Vectorized Control Flow Graph

```
<bb 2>:
  vect_pa.10_26 = &a[4];
  vect_pa.15_30 = &a;
<bb 3>:
  # vect_pa.7_27 = PHI <vect_pa.7_28,
                        vect_pa.10_26>
  # vect_pa.12_31 = PHI <vect_pa.12_32,
                        vect_pa.15_30>
  vect_var_.11_29 = MEM[vect_pa.7_27];
  MEM[vect_pa.12_31] = vect_var_.11_29;
  vect_pa.7_28 = vect_pa.7_27 + 16;
  vect_pa.12_32 = vect_pa.12_31 + 16;
  ivtmp.16_34 = ivtmp.16_33 + 1;
  if (ivtmp.16_34 < 154)
    goto <bb 4>;
```

Example 3: Vectorization but No Parallelization

Step 2: Examining vectorization

Control Flow Graph

```
<bb 3>:
  # i_12 = PHI <i_5(4), 0(2)>
  D.2834_3 = i_12 + 4;
  D.2835_4 = a[D.2834_3];
  a[i_12] = D.2835_4;
  i_5 = i_12 + 1;
  if (i_5 != 619)
    goto <bb 4>;
  else
    goto <bb 5>;
<bb 4>:
  goto <bb 3>;
```

Vectorized Control Flow Graph

```
<bb 2>:
  vect_pa.10_26 = &a[4];
  vect_pa.15_30 = &a;
<bb 3>:
  # vect_pa.7_27 = PHI <vect_pa.7_28,
                       vect_pa.10_26>
  # vect_pa.12_31 = PHI <vect_pa.12_32,
                       vect_pa.15_30>
  vect_var_.11_29 = MEM[vect_pa.7_27];
  MEM[vect_pa.12_31] = vect_var_.11_29;
  vect_pa.7_28 = vect_pa.7_27 + 16;
  vect_pa.12_32 = vect_pa.12_31 + 16;
  ivtmp.16_34 = ivtmp.16_33 + 1;
  if (ivtmp.16_34 < 154)
    goto <bb 4>;
```

Example 3: Vectorization but No Parallelization

- Step 3: Observing the conclusion about dependence information

```
inner loop index: 0
loop nest: (1 )
distance_vector: 4
direction_vector: +
```

- Step 4: Observing the final decision about parallelization

```
FAILED: data dependencies exist across iterations
```

Example 4: No Vectorization and No Parallelization

Step 0: Compiling the code with `-O3`

```
int a[256], b[256];
int main ()
{
    int i;
    for (i=0; i<216; i++)
    {
        a[i+2] = b[i] + 5;
        b[i+3] = a[i] + 10;
    }
    return 0;
}
```

- Additional options for parallelization
  `-ftree-parallelize-loops=2 -fdump-tree-parloops-all`
- Additional options for vectorization
  `-fdump-tree-vect-all -msse4`

Example 4: No Vectorization and No Parallelization

- Step 1: Observing the final decision about vectorization

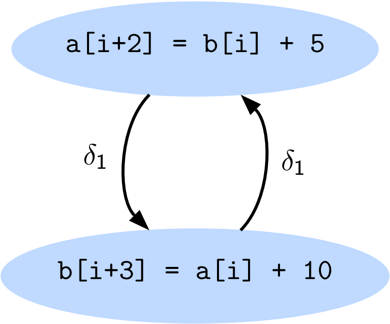
```
noparvec.c:5: note: vectorized 0 loops in function.
```

- Step 2: Observing the final decision about parallelization

```
FAILED: data dependencies exist across iterations
```

Example 4: No Vectorization and No Parallelization

Step 3: Understanding the dependencies that prohibit vectorization and parallelization



Advanced Issues in Vectorization

Alignment by Peeling

```
int a[256];
int main ()
{
   int i;
   for (i=4; i<253; i++)
      a[i-3] = a[i-3] + a[i+2];
}
```

Advanced Issues in Vectorization

Alignment by Peeling

```
int a[256];
int main ()
{
   int i;
   for (i=4; i<253; i++)
      a[i-3] = a[i-3] + a[i+2];
}
```

a[1] = a[1] + a[6]

Advanced Issues in Vectorization

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}
```

`a[1] = a[1] + a[6]`

Peel Factor = 3

Advanced Issues in Vectorization

Alignment by Peeling

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int a[256];
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}
```

`a[1] = a[1] + a[6]`

Peel Factor $= 3$

Advanced Issues in Vectorization

Alignment by Peeling

```
int a[256];
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      a[i-3] = a[i-3] + a[i+2];
}
```

`a[1] = a[1] + a[6]`

Peel Factor $= 2$

Advanced Issues in Vectorization

Alignment by Peeling

```
int a[256];
int main ()
{
   int i;
   for (i=4; i<253; i++)
      a[i-3] = a[i-3] + a[i+2];
}
```

```
a[1] = a[1] + a[6]
```

Maximize alignment with minimal peel factor

Advanced Issues in Vectorization

Alignment by Peeling

```
int a[256];
int main ()
{
   int i;
   for (i=4; i<253; i++)
      a[i-3] = a[i-3] + a[i+2];
}
```

Peel the loop by 3

Advanced Issues in Vectorization

An aligned vectorized code can consist of three parts

- Peeled Prologue - Scalar code for alignment
- Vectorized body - Iterations that are vectorized
- Epilogue - Residual scalar iterations

Advanced Issues in Vectorization

Loop Versioning

How do we vectorize a loop that has

- unaligned data references
- undetermined data dependence relation

```
int a[256];
int main ()
{
   int i;
   for (i=0; i<100; i++)
      a[i] = a[i*2];
}
```

Advanced Issues in Vectorization

Loop Versioning

How do we vectorize a loop that has

- unaligned data references
- undetermined data dependence relation

```
int a[256];
int main ()
{
   int i;
   for (i=0; i<100; i++)
      a[i] = a[i*2];
}
```

```
"Bad distance vector for a[i] and a[i*2]"
```

Advanced Issues in Vectorization

- Generate two versions of the loop, one which is vectorized and one which is not.
- A test is then generated to control the execution of desired version. The test checks for the alignment of all of the data references that may or may not be aligned.
- An additional sequence of runtime tests is generated for each pairs of data dependence relations whose independence was undetermined or unproven.
- The vectorized version of loop is executed only if both alias and alignment tests are passed.

When to Vectorize?

Vectorization is profitable when

$$SIC * niters + SOC > VIC * \left(\frac{niters - PL\_ITERS - EP\_ITERS}{VF}\right) + VOC$$

`SIC` = scalar iteration cost
`VIC` = vector iteration cost
`VOC` = vector outside cost
`VF` = vectorization factor
`PL_ITERS` = prologue iterations
`EP_ITERS` = epilogue iterations
`SOC` = scalar outside cost

Part 2

Loop Transformations in Polytope Model

Problems with Classical Loop Nest Transforms

Loop nest optimization is a combinatorial problem. Due to the growing complexity of modern architectures, it involves two increasingly difficult tasks:

- Analyzing the profitability of sequences of transformations to enhance parallelism, locality, and resource usage
- the construction and exploration of search space of legal transformation sequences

Problems with Classical Loop Nest Transforms

Loop nest optimization is a combinatorial problem. Due to the growing complexity of modern architectures, it involves two increasingly difficult tasks:

- Analyzing the profitability of sequences of transformations to enhance parallelism, locality, and resource usage
- the construction and exploration of search space of legal transformation sequences

Practical optimizing and parallelizing compilers restore to a predefined set of enabling

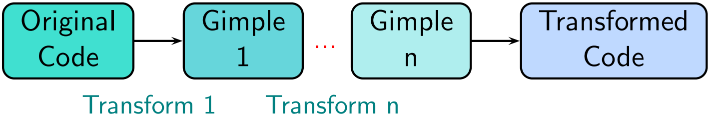
Problems with Classical Loop Nest Transforms

Loop transformations on Lambda Framework were discontinued in gcc-4.6.0 for the following reasons:

- Difficult to undo loop transformations - transforms are applied on the syntactic form
- Difficult to compose transformations - intermediate translation to a syntactic form is necessary after each transformation
- Ordering of transformations is fixed

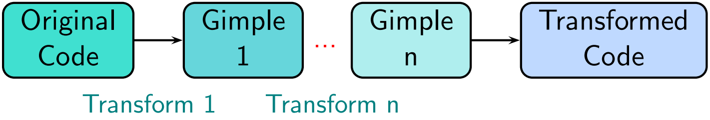
Problems with Classical Loop Nest Transforms

Traditional Loop Transforms:

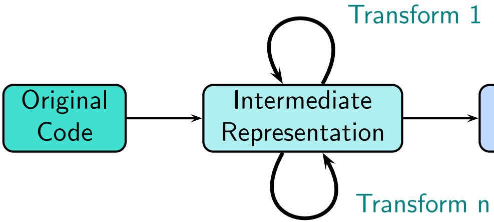


Problems with Classical Loop Nest Transforms

Traditional Loop Transforms:



Expected Loop Transforms with Composition:



Requirement

GCC requires a rich algebraic representation that

- Provides a solution to *phase-ordering* problem - facilitate efficient exploration and configuration of multiple transformation sequences
- Decouples the transformations from the syntatic form of program, avoiding code size explosion
- Performs only legal transformation sequences
- Provides precise performance models and profitability prediction heuristics

Solution : Polyhedral Representation

- Polytope Model is a mathematical framework for loop nest optimizations
- The loop bounds parametrized as inequalities form a convex polyhedron
- An affine scheduling function specifies the scanning order of integral points

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```
for (i=1; i<=n; i++)
    for (j=1; j<=n; j++)
       if (i<=n-j+2)
          S1;
```

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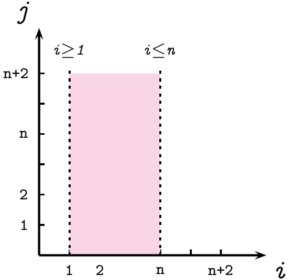

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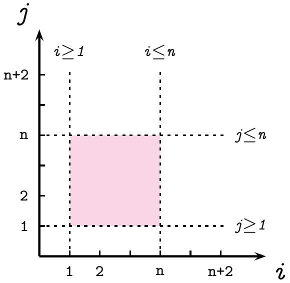

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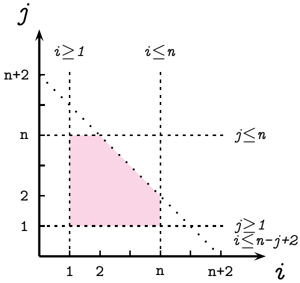

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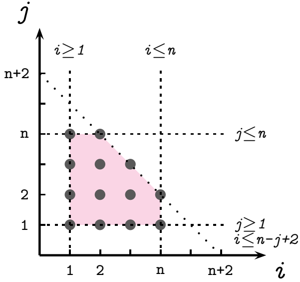

GRAPHITE

GRAPHITE is the interface for polyhedra representation of GIMPLE

goal: more high level loop optimizations

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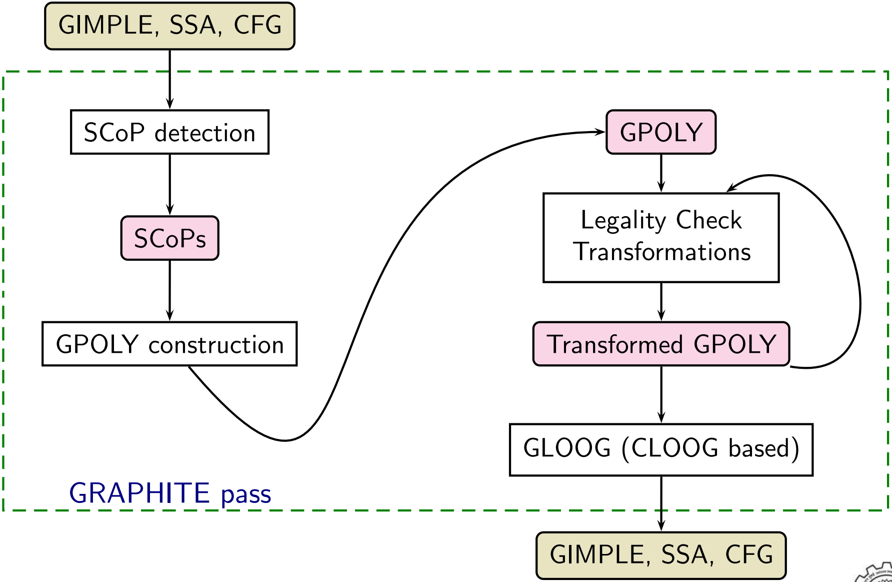
GRAPHITE is the interface for polyhedra representation of GIMPLE

goal: more high level loop optimizations

Tasks of GRAPHITE Pass:

- Extract the *polyhedral model* representation out of GIMPLE
- Perform the various optimizations and analyses on this polyhedral model representation
- Regenerate the GIMPLE three-address code that corresponds to transformations on the polyhedral model

Compilation Workflow



What Code Can be Represented?

The target of polyhedral representation are sequence of loop nests with

- Affine loop bounds (e.g. i $<$ 4$*$n$+$4$*$j-1)
- Affine array accesses (e.g. A[3i$+$1])
- Constant loop strides (e.g. i $+=$ 2)
- Conditions containing comparisons ($<$,$\leq$,$>$,$\geq$,$==$,!$=$) between affine functions
- Invariant global parameters

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- Invariant global parameters

Non-rectangular, non-perfectly nested loops are also represented polyhedrally for optimization

GPOLY

GPOLY : the polytope representation in GRAPHITE, currently implemented by the Parma Polyhedra Library (PPL)

- SCoP - The optimization unit (e.g. a loop with some basic blocks)
  scop := ([*black box*])
- Black Box - An operation (e.g. basic block with one or more statements) where the memory accesses are known
  black box := (*iteration domain*, *scattering matrix*, [*data reference*])
- Iteration Domain - The set of loop iterations for the black box
- Data Reference - The memory cells accessed by the black box
- Scattering Matrix - Defines the execution order of statement iterations (e.g. schedule)

Building SCoPs

- SCoPs built on top of the CFG
- Basic blocks with side-effect statements are split
- All basic blocks belonging to a SCoP are dominated by entry, and postdominated by exit of the SCoP

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```
int a[256][256], b[245], c[145], n;
int main ()
{
    int i, j;
    for (i=0; i<n; i++) {
        for (j=0; j<62; j++) {
            a[i][j] = a[i+1][j+2];
            a[j][i+7] = b[j];
        }
        c[i] = a[i][i+14];
    }
}
```

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global parameter

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SCoP

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        }
        c[i] = a[i][i+14];
    }
}
```

global parameter

SCoP

bbs 1

bbs 2

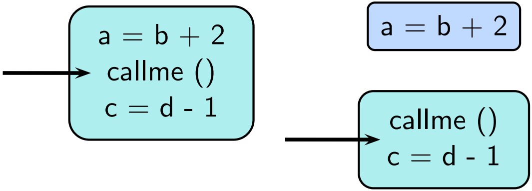
Example : Building SCoPs

Splitting basic blocks:

```
a = b + 2
callme ()
c = d - 1
```

Example : Building SCoPs

Splitting basic blocks:



Example : Building SCoPs

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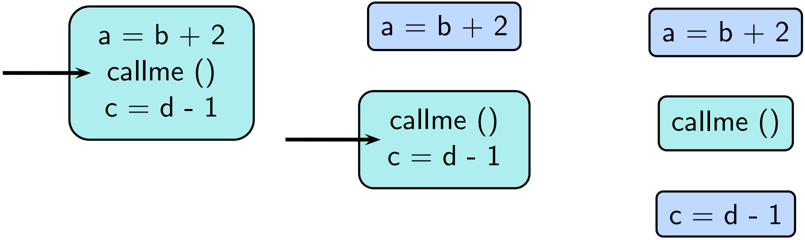

Polyhedral Representation of a SCoP

The statements and parametric affine inequalities can be expressed by:

- Iteration Domain (bounds of enclosing loops)

$$\mathcal{D}^S = \{\texttt{i} \mid \mathcal{D}^S \times (\texttt{i},\texttt{g},\texttt{1})^T \geq 0\}$$

```
for (i=0; i<m; i++)
    for (j=5; j<n; j++)
        A[2*i][j+1] = ...;
```

$$\begin{bmatrix} \texttt{i} & \texttt{j} & \texttt{m} & \texttt{n} & \texttt{cst} \\ \hline & & & & \\ & & & & \end{bmatrix} \geq 0$$

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```

$$\begin{array}{ccccc} \mathtt{i} & \mathtt{j} & \mathtt{m} & \mathtt{n} & \mathtt{cst} \end{array}$$
$$\left[\begin{array}{ccccc} 1 & 0 & 0 & 0 & 0 \\ & & & & \\ & & & & \end{array}\right] \geq 0$$

$\mathtt{i} \geq 0$

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```

$$\begin{array}{ccccc} i & j & m & n & cst \end{array}$$
$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & -1 \\ & & & & \\ & & & & \end{bmatrix} \geq 0$$

$\texttt{i} \leq \texttt{m - 1}$

Polyhedral Representation of a SCoP

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```

$$\begin{array}{c} \begin{array}{ccccc} \mathtt{i} & \mathtt{j} & \mathtt{m} & \mathtt{n} & \mathtt{cst} \end{array} \\ \left[\begin{array}{ccccc} 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & -1 \\ 0 & 1 & 0 & 0 & -5 \end{array}\right] \geq 0 \end{array}$$

$\mathtt{j} \geq 5$

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$$\begin{array}{ccccc} \mathtt{i} & \mathtt{j} & \mathtt{m} & \mathtt{n} & \mathtt{cst} \end{array}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & -1 \\ 0 & 1 & 0 & 0 & -5 \\ 0 & -1 & 0 & 1 & -1 \end{bmatrix} \geq 0$$

$\mathtt{j} \leq \mathtt{n - 1}$

Polyhedral Representation of a SCoP

The statements and parametric affine inequalities can be expressed by:

- Iteration Domain (bounds of enclosing loops)
- Data Reference (a list of access functions)

$$\mathcal{F} = \{(\mathtt{i,a,s}) \mid \mathcal{F} \times (\mathtt{i,a,s,g,1})^T \geq 0\}$$

```
for (i=1; i<m; i++)
   for (j=5; j<n; j++)
      A[2*i][j+1] = ...;
```

$$\left[\begin{array}{ccccc} \mathtt{i} & \mathtt{j} & \mathtt{m} & \mathtt{n} & \mathtt{cst} \\ \hline & & & & \\ \end{array}\right]$$

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   for (j=5; j<n; j++)
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```

$$\begin{array}{ccccc} \mathtt{i} & \mathtt{j} & \mathtt{m} & \mathtt{n} & \mathtt{cst} \end{array}$$
$$\left[\begin{array}{ccccc} 2 & 0 & 0 & 0 & 0 \\ & & & & \end{array}\right]$$

$2 * \mathtt{i}$

Polyhedral Representation of a SCoP

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j + 1

Polyhedral Representation of a SCoP

The statements and parametric affine inequalities can be expressed by:

- Iteration Domain (bounds of enclosing loops)
- Data Reference (a list of access functions)
- Scattering Function (scheduling order)

$$\theta = \{(\texttt{t,i}) \mid \theta \times (\texttt{t,i,g,1})^T \geq \texttt{0}\}$$

sequence [s_1, s_2]:
$\mathcal{S}[s_1] = \mathrm{t}$, $\mathcal{S}[s_2] = \mathrm{t} + 1$

loop [$loop_1\ s\ end_1$] : i_1 indexes loop_1 iterations
$\mathcal{S}[loop_1] = \mathrm{t}$, $\mathcal{S}[s] = (\mathrm{t}, \mathrm{i}_1, 0)$

Polyhedral Representation of a SCoP

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$$\theta = \{(\mathtt{t,i}) \mid \theta \times (\mathtt{t,i,g,1})^T \geq 0\}$$

```
for (i=1;i<=N;i++) {
   for (j=1;j<=i-1;j++) {
      a[i][i] -= a[i][j];
      a[j][i] += a[i][j];
   }
   a[i][i] = sqrt(a[i][i]);
}
```

Scattering Function

$$\theta_{S1}(i,j)^T = (0,i,0,j,0)^T$$

Polyhedral Representation of a SCoP

The statements and parametric affine inequalities can be expressed by:

- Iteration Domain (bounds of enclosing loops)
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```
for (i=1;i<=N;i++) {
   for (j=1;j<=i-1;j++) {
      a[i][i] -= a[i][j];
      a[j][i] += a[i][j];
   }
   a[i][i] = sqrt(a[i][i]);
}
```

Scattering Function

$$\theta_{S2}(i,j)^T = (0,i,0,j,1)^T$$

Polyhedral Representation of a SCoP

The statements and parametric affine inequalities can be expressed by:

- Iteration Domain (bounds of enclosing loops)
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```
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      a[i][i] -= a[i][j];
      a[j][i] += a[i][j];
   }
   a[i][i] = sqrt(a[i][i]);
}
```

Scattering Function

$\theta_{S3}(i,j)^T = (0,i,1)^T$

Polyhedral Dependence Analysis in GRAPHITE

- An *instancewise dependence analysis* - dependences between source and sink represented as polyhedra
- Scalar dependences are treated as zero-dimensional arrays
- Global parameters are handled
- Can take care of conditional and some form of triangular loops, as the information can be safely integrated with the iteration domain
- High cost, and therefore dependence is computed only to validate a transformation

Legality of Transformations

Original Code

```
int A[256][256];
int main ()
{
   for (j=0; j<n; j++){
       for (i=0; i<n; i++){
            A[i][j] = A[j][i];
       }
   }
}
```

$pdr_0 =$ `A[j][i]`
$pdr_1 =$ `A[i][j]`

Memory location `A[0][1]` is read at pdr_0 when $j = 0$ and later written at pdr_1 when $j = 1$

Dependence : Write after Read

Legality of Transformations

Original Code

```
int A[256][256];
int main ()
{
    for (j=0; j<n; j++){
        for (i=0; i<n; i++){
            A[i][j] = A[j][i];
        }
    }
}
```

Loop Interchange

```
int A[256][256];
int main ()
{
    for (i=0; j<n; i++){
        for (j=0; j<n; j++){
            A[i][j] = A[j][i];
        }
    }
}
```

Are the dependences preserved after the transformation?

Legality of Transformations

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int A[256][256];
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   for (j=0; j<n; j++){
      for (i=0; i<n; i++){
          A[i][j] = A[j][i];
      }
   }
}
```

Loop Interchange

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int A[256][256];
int main ()
{
   for (i=0; j<n; i++){
      for (j=0; j<n; j++){
          A[i][j] = A[j][i];
      }
   }
}
```

Are the dependences preserved after the transformation?

No! `A[0][1]` is first written at pdr_1 when i $=0$, and then read at pdr_0 when i $=1$

Dependence : Read after Write

Legality of Transformations

- A transformation is legal if the dependences are preserved - for any dependence instance, the source and sink remain same across transformation
- If the dependence is reversed, source becomes sink and sink becomes source in the transformed space
- GRAPHITE captures this notion in *Violated Dependence Analysis*. A reverse data dependence polyhedron is constructed in the transformed scattering from sink to source, and it is intersected with the original polyhedron
- If the intersection is non-empty, atleast one pair of iterations is executed in wrong order, rendering the transformation illegal

Parallelization with GRAPHITE

- The GRAPHITE pass without optimizations is run (`GIMPLE` $\rightarrow$ `POLY` $\rightarrow$ `GIMPLE`)
- During this conversion, data dependence is performed using *instancewise data dependence analysis*
- This dependence result is used to determine if the loop can be parallelized

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- Stronger dependence analysis, can detect parallelism in loops with invariant parameters
- Conditional loops and some triangular loops can be parallelized after loop distribution

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`Extra Compilation flag : -floop-parallelize-all`

Loop Tranformations in GRAPHITE

Loop transforms implemented in GRAPHITE:

- loop interchange
- loop blocking and loop stripmining
- loop flattening

These transformations are mostly used to improve scope of parallelization or vectorization. Application of such transformations must not violate the dependences

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- loop flattening

These transformations are mostly used to improve scope of parallelization or vectorization. Application of such transformations must not violate the dependences

Cost Model:

- Cost models are used to check the profitability of transformation.
- For example, loops are interchanged only if the sum total of inner loop's strides are greater than the outer loop

Loop Interchange in GRAPHITE

Original Code

```
int A[256][256];
int main ()
{
   for (j=0; j<n; j++){
      for (i=1; i<n; i++){
           A[i][j] = A[i-1][j];
      }
   }
}
```

Strides of i $= 255 + 255 = 510$

Strides of j $= 1 + 1 = 2$

Since strides of i $>$ strides of j, interchange loop i with j

Loop Interchange in GRAPHITE

Original Code

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int A[256][256];
int main ()
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    for (j=0; j<n; j++){
        for (i=1; i<n; i++){
            A[i][j] = A[i-1][j];
        }
    }
}
```

After Interchange

```
int A[256][256];
int main ()
{
    for (i=1; i<n; i++){
        for (j=0; j<n; j++){
            A[i][j] = A[i-1][j];
        }
    }
}
```

outermost loop has the largest stride

Loop Interchange in GRAPHITE

Original Code

```
for (i=1; i<n; i++){
   for (j=0; j<n; j++){
       A[i][j] = A[i-1][j]
   }
}
```

Outer Loop - dependence on i, can not be parallelized

Inner Loop - parallelizable, but synchronization barrier required

Total number of times synchronization executed = n

Loop Interchange in GRAPHITE

Original Code

```
for (i=1; i<n; i++){
   for (j=0; j<n; j++){
       A[i][j] = A[i-1][j]
   }
}
```

After Interchange

```
for (j=0; i<n; i++){
   for (i=1; j<n; j++){
       A[i][j] = A[i-1][j]
   }
}
```

Outer Loop - parallelizable

Total number of times synchronization executed $= 1$

Loop Interchange in GRAPHITE

Original Code

```
for (i=1; i<n; i++){
   for (j=0; j<n; j++){
       A[i][j] = A[i-1][j]
   }
}
```

After Interchange

```
for (j=0; i<n; i++){
   for (i=1; j<n; j++){
       A[i][j] = A[i-1][j]
   }
}
```

Outer Loop - parallelizable

Total number of times synchronization executed = 1

Is this loop interchange profitable in GRAPHITE?

Loop Regeneration

- *Chunky Loop Generator* (CLooG) is used to regenerate the loop
- It scans the integral points of the polyhedra to recreate loop bounds

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Original Program

```
for (i=0; i<250; i++)
   for (j=0; j<200; j++) {
      if (j < k+3)
         S1;
   }
```

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for (i=0; i<250; i++)
    for (j=0; j<200; j++) {
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```

Loop generated by CLooG

```
for (i=0; i<=249; i++) {
    for (j=0; j<=min(k+2,199); j++) {
        S1;
    }
}
```

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for (i=0; i<=249; i++) {
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Merge conditional code with loop bounds if possible

GRAPHITE Conclusions

Advantages of GRAPHITE

- Better data dependence analysis - handles conditional codes, parametric invariants
- Makes auto-parallelization more efficient
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Future Scope

- Making instancewise dependence analysis algorithmically cheaper
- Automating the search most profitable transform composition sequence
- Developing efficient cost models
- Exploring scalability issues

Parallelization and Vectorization in GCC : Conclusions

- Chain of recurrences seems to be a useful generalization
- Interaction between different passes is not clear due to fixed order
- Auto-vectorization and auto-parallelization can be improved by enhancing the dependence analysis framework
- Efficient cost models are needed to automate legal transformation composition
- GRAPHITE seems to be a promising mathematical abstraction

Last but not the least ...

Thank You!