Workshop on Essential Abstractions in GCC

Parallelization and Vectorization in GCC

GCC Resource Center
(www.cse.iitb.ac.in/grc)

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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

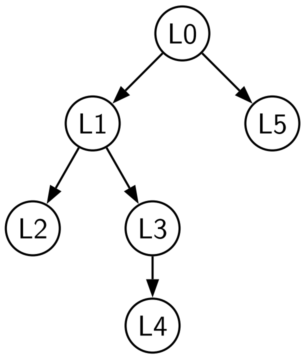
Implementation Issues

- 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

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 ⟨Starting Value, modification, stride⟩

```
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;
}
```

{&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 2: Understanding the chain of recurrences

```
<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>;
```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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)>
  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>;
```

```
(scalar_evolution = {0, +, 1}_1)
```


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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)>
  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>;
```

```
(scalar_evolution = {1, +, 1}_1)
```


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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)>
  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>;
```

```
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

```
<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>;
```

```
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
• Solve for $0 \leq x, y < 150$
$y = x + 1$
$\Rightarrow x - y + 1 = 0$
• Find min and max of LHS
$x - y + 1$
Min: -148 Max: +150
RHS belongs to $[-148, +150]$ and dependence may exist
	• `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
	• 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	Control Flow Graph

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

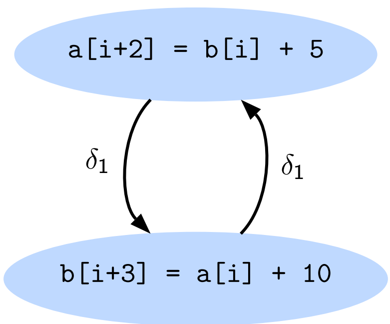
  `noparvec.c:5: note: vectorized 0 loops in function.`

- Step 2: Observing the final decision about parallelization

  `FAILED: data dependencies exist across iterations`

Example 4: No Vectorization and No Parallelization

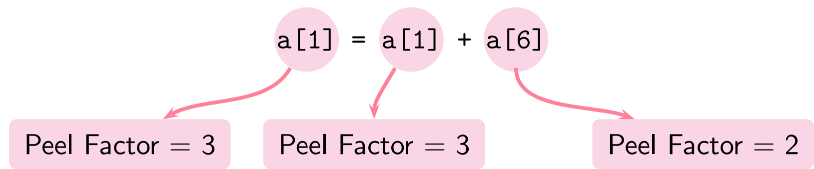
Step 3: Understanding the dependencies that prohibit vectorization and parallelization



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]
```

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];
}
```

```
"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

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

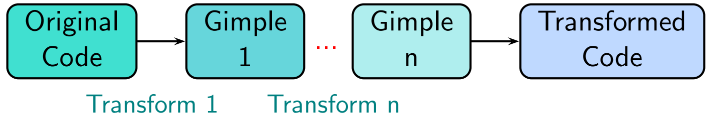
Problems with Classical Loop Nest Transforms

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

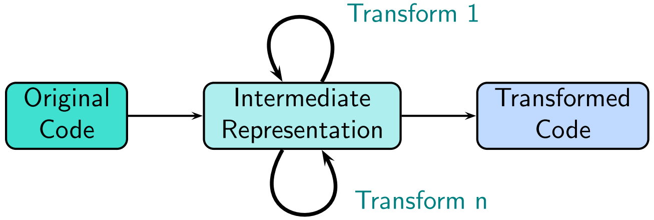
- Difficult to undo loop transformations - transforms are applied on the syntactic form
- Difficult to compose transformations - intermediate translation to a syntactic form is necessary after each transformation
- Ordering of transformations is fixed

Problems with Classical Loop Nest Transforms

Traditional Loop Transforms:



Expected Loop Transforms with Composition:



Requirement

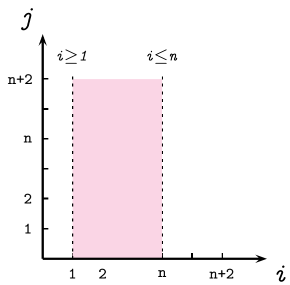
GCC requires a rich algebraic representation that

- 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

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



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          S1;
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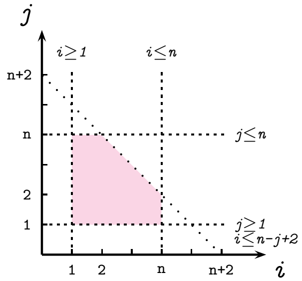

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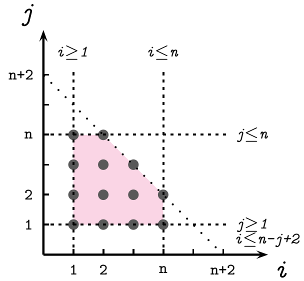


GRAPHITE

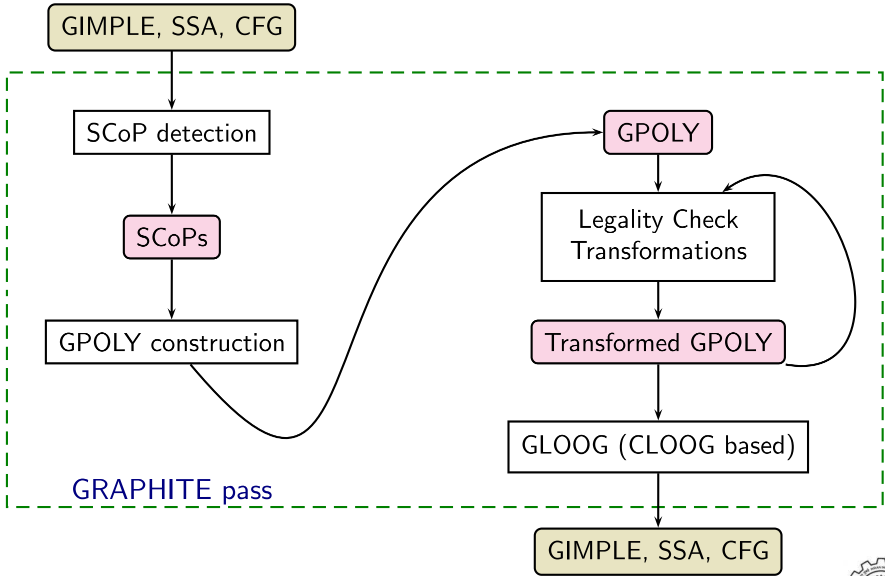
GRAPHITE is the interface for polyhedra representation of GIMPLE

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

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

```
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];
   }
}
```

global parameter

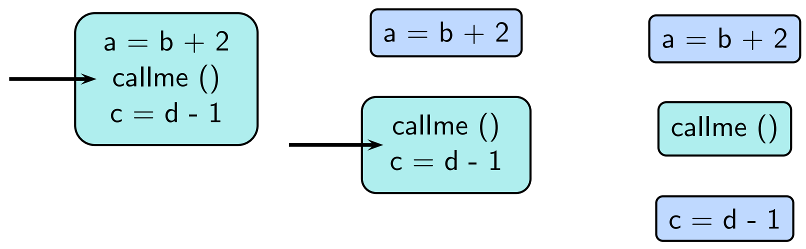
SCoP

bbs 1

bbs 2

Example : Building SCoPs

Splitting basic blocks:



Polyhedral Representation of a SCoP

The statements and parametric affine inequalities can be expressed by:

- Iteration Domain (bounds of enclosing loops)

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

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

i	j	m	n	cst

≥ 0

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

i	j	m	n	cst
1	0	0	0	0

≥ 0

i ≥ 0

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

i	j	m	n	cst
1	0	0	0	0
−1	0	1	0	−1

≥ 0

i ≤ m - 1

Polyhedral Representation of a SCoP

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

i	j	m	n	cst
1	0	0	0	0
−1	0	1	0	−1
0	1	0	0	−5

≥ 0

j ≥ 5

Polyhedral Representation of a SCoP

The statements and parametric affine inequalities can be expressed by:

- Iteration Domain (bounds of enclosing loops)

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

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

i	j	m	n	cst
1	0	0	0	0
−1	0	1	0	−1
0	1	0	0	−5
0	−1	0	1	−1

≥ 0

j ≤ 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)

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

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

i	j	m	n	cst

Polyhedral Representation of a SCoP

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

i	j	m	n	cst
2	0	0	0	0

2 * i

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)

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

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

i	j	m	n	cst
2	0	0	0	0
0	1	0	0	1

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)

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

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

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

3 July 2011 gcc-par-vect: Loop Transformations in Polytope Model 48/62

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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- Scattering Function (scheduling order)

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

```
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

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

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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)
- Data Reference (a list of access functions)
- Scattering Function (scheduling order)

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

```
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

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

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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)
- Data Reference (a list of access functions)
- Scattering Function (scheduling order)

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

```
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

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

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?
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 → POLY → 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

Benefits:

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

`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

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

```
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];
        }
    }
}
```

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

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

Original Program

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

Loop generated by CLooG

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

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
- Composition of transforms is possible

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!