Workshop on Essential Abstractions in GCC

First Level Gray Box Probing

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

Department of Computer Science and Engineering,
Indian Institute of Technology, Bombay

July 2010

Outline

- Introduction to Graybox Probing of GCC
- Examining GIMPLE Dumps
  - Translation of data accesses
  - Translation of intraprocedural control flow
  - Translation of interprocedural control flow
- Examining RTL Dumps
- Examining Assembly Dumps
- Conclusions

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Outline

Notes

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Part 1

Preliminaries

Notes

What is Gray Box Probing of GCC?

- Black Box probing:
  Examining only the input and output relationship of a system
- White Box probing:
  Examining internals of a system for a given set of inputs
- Gray Box probing:
  Examining input and output of various components/modules
  - Overview of translation sequence in GCC
  - Overview of intermediate representations
  - Intermediate representations of programs across important phases

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What is Gray Box Probing of GCC?

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First Level Gray Box Probing of GCC

- Restricted to the most important translations in GCC

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First Level Gray Box Probing of GCC

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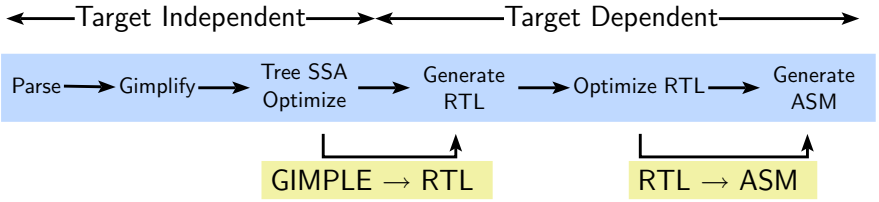
Basic Transformations in GCC

Tranformation from a language to a *different* language



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Basic Transformations in GCC

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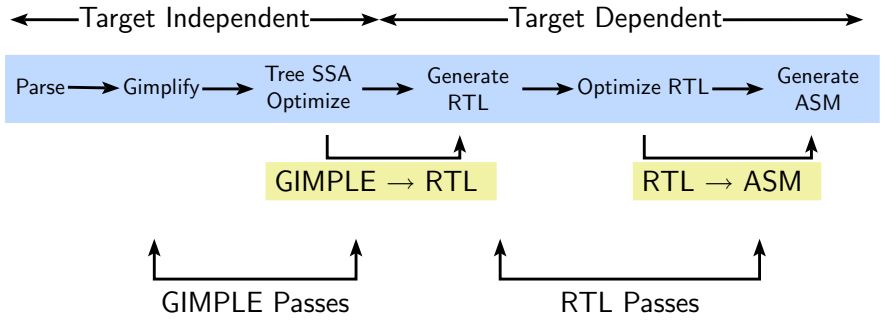
Basic Transformations in GCC

Tranformation from a language to a *different* language



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Basic Transformations in GCC

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Transformation Passes in GCC 4.5.0

- A total of 203 unique pass names initialized in `${SOURCE}/gcc/passes.c`
  Total number of passes is 239.
  - Some passes are called multiple times in different contexts
    Conditional constant propagation and dead code elimination are called thrice
  - Some passes are enabled for specific architectures
  - Some passes have many variations (eg. special cases for loops)
    Common subexpression elimination, dead code elimination
- The pass sequence can be divided broadly in two parts
  - Passes on GIMPLE
  - Passes on RTL
- Some passes are organizational passes to group related passes

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Transformation Passes in GCC 4.5.0

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Passes On GIMPLE in GCC 4.5.0

Pass Group	Examples	Number of passes
Lowering	GIMPLE IR, CFG Construction	12
Interprocedural Optimizations	Conditional Constant Propagation, Inlining, SSA Construction, LTO	49
Intraprocedural Optimizations	Constant Propagation, Dead Code Elimination, PRE	42
Loop Optimizations	Vectorization, Parallelization	27
Remaining Intraprocedural Optimizations	Value Range Propagation, Rename SSA	23
Generating RTL		01
Total number of passes on GIMPLE		154

Passes On GIMPLE in GCC 4.5.0

Notes

Passes On RTL in GCC 4.5.0

Pass Group	Examples	Number of passes
Intraprocedural Optimizations	CSE, Jump Optimization	21
Loop Optimizations	Loop Invariant Movement, Peeling, Unswitching	7
Machine Dependent Optimizations	Register Allocation, Instruction Scheduling, Peephole Optimizations	54
Assembly Emission and Finishing		03
Total number of passes on RTL		85

Passes On RTL in GCC 4.5.0

Notes

Finding Out List of Optimizations

Along with the associated flags

- A complete list of optimizations with a brief description

  `gcc -c --help=optimizers`

- Optimizations enabled at level 2 (other levels are 0, 1, 3, and s)

  `gcc -c -O2 --help=optimizers -Q`

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Finding Out List of Optimizations

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Producing the Output of GCC Passes

- Use the option `-fdump-<ir>-<passname>`

  `<ir>` could be
  - `tree`: Intraprocedural passes on GIMPLE
  - `ipa`: Interprocedural passes on GIMPLE
  - `rtl`: Intraprocedural passes on RTL
- Use `all` in place of `<pass>` to see all dumps
  Example: `gcc -fdump-tree-all -fdump-rtl-all test.c`
- Dumping more details:
  Suffix `raw` for tree passes and `details` or `slim` for RTL passes
  Individual passes may have more verbosity options (e.g. `-fsched-verbose=5`)
- Use `-S` to stop the compilation with assembly generation
- Use `--verbose-asm` to see more detailed assembly dump

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Producing the Output of GCC Passes

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Dumps for Our Code Fragments

GIMPLE dumps (t)

001t.tu
003t.original
004t.gimple
006t.vcg
008t.omplower
009t.lower
011t.eh
012t.cfg
013t.veclower
014t.inline_param1
021t.cleanup_cfg
023t.ssa
024t.einline2
040t.release_ssa
041t.inline_param3
135t.cplxlower0
140t.optimized
219t.statistics

ipa dumps (i)

000i.cgraph
015i.visibility
019i.early_local_cleanups
044i.whole-program
046i.inline

rtl dumps (r)

141r.expand
142r.sibling
144r.initvals
145r.unshare
146r.vregs
147r.into_cfglayout
148r.jump
160r.reginfo
180r.outof_cfglayout
181r.split1
183r.dfinit
184r.mode_sw
185r.asmcons
188r.ira
191r.split2
193r.pro_and_epilogue
206r.stack
207r.alignments
210r.mach
211r.barriers
215r.shorten
216r.nothrow
217r.final
218r.dfinish

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Dumps for Our Code Fragments

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Total Number of Dumps

Optimization Level	Number of Dumps	Goals
Default	47	Fast compilation
O1	134	
O2	156	
O3	165	
Os	154	Optimize for space

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Total Number of Dumps

Notes

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Selected Dumps for Our Example Program

GIMPLE dumps (t)
001t.tu
003t.original
004t.gimple
006t.vcg
008t.omplower
009t.lower
011t.eh
012t.cfg
013t.veclower
014t.inline_param1
021t.cleanup_cfg
023t.ssa
024t.einline2
040t.release_ssa
041t.inline_param3
135t.cplxlower0

140t.optimized
219t.statistics

ipa dumps (i)
000i.cgraph
015i.visibility
019i.early_local_cleanups
044i.whole-program
046i.inline

rtl dumps (r)
141r.expand
142r.sibling
144r.initvals
145r.unshare
146r.vregs
147r.into_cfglayout
148r.jump
160r.reginfo

180r.outof_cfglayout
181r.split1
183r.dfinit
184r.mode_sw
185r.asmcons
188r.ira
191r.split2
193r.pro_and_epilogue
206r.stack
207r.alignments
210r.mach
211r.barriers
215r.shorten
216r.nothrow
217r.final
218r.dfinish
assembly output

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Selected Dumps for Our Example Program

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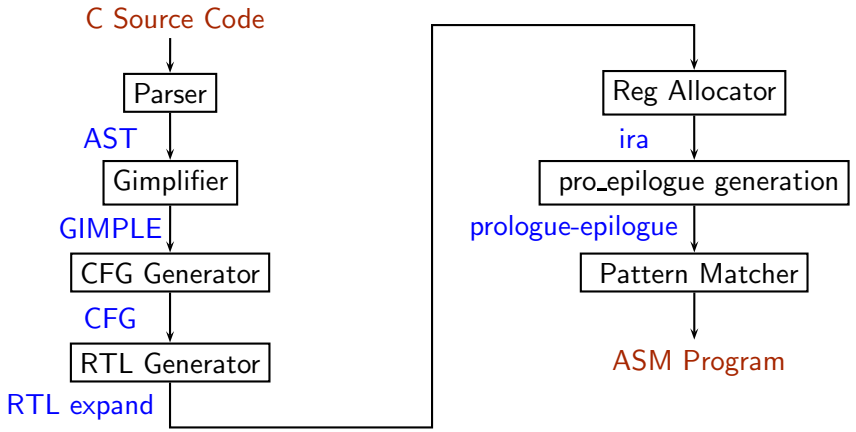
Passes for First Level Graybox Probing of GCC



Lowering of abstraction!

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Passes for First Level Graybox Probing of GCC

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Part 2

Examining GIMPLE Dumps

Notes

Notes

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Gimplifier

- About GIMPLE
  - Three-address representation derived from GENERIC
    Computation represented as a sequence of basic operations
    Temporaries introduced to hold intermediate values
  - Control construct are explicated into conditional jumps
- Examining GIMPLE Dumps
  - Examining translation of data accesses
  - Examining translation of control flow
  - Examining translation of function calls

Notes

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GIMPLE: Composite Expressions Involving Local and Global Variables

test.c

```
int a;

int main()
{
  int x = 10;
  int y = 5;

  x = a + x * y;
  y = y - a * x;

}
```

test.c.004t.gimple

```
x = 10;
y = 5;
D.1954 = x * y;
a.0 = a;
x = D.1954 + a.0;
a.1 = a;
D.1957 = a.1 * x;
y = y - D.1957;
```

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GIMPLE: Composite Expressions Involving Local and Global Variables

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GIMPLE: 1-D Array Accesses

test.c

```
int main()
{
  int a[3], x;
  a[1] = a[2] = 10;
  x = a[1] + a[2];
  a[0] = a[1] + a[1]*x;
}
```

test.c.004t.gimple

```
a[2] = 10;
D.1952 = a[2];
a[1] = D.1952;
D.1953 = a[1];
D.1954 = a[2];
x = D.1953 + D.1954;
D.1955 = x + 1;
D.1956 = a[1];
D.1957 = D.1955 * D.1956;
a[0] = D.1957;
```

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GIMPLE: 1-D Array Accesses

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GIMPLE: 2-D Array Accesses

test.c

```
int main()
{
  int a[3][3], x, y;
  a[0][0] = 7;
  a[1][1] = 8;
  a[2][2] = 9;
  x = a[0][0] / a[1][1];
  y = a[1][1] % a[2][2];
}
```

test.c.004t.gimple

```
 a[0][0] = 7;
 a[1][1] = 8;
 a[2][2] = 9;
 D.1953 = a[0][0];
 D.1954 = a[1][1];
 x = D.1953 / D.1954;
 D.1955 = a[1][1];
 D.1956 = a[2][2];
 y = D.1955 % D.1956;
```

GIMPLE: 2-D Array Accesses

Notes

GIMPLE: Use of Pointers

test.c

```
int main()
{
  int **a,*b,c;
  b = &c;
  a = &b;
  **a = 10;  /* c = 10 */
}
~
```

test.c.004t.gimple

```
main ()
{
  int * D.1953;
  int * * a;
  int * b;
  int c;

  b = &c;
  a = &b;
  D.1953 = *a;
  *D.1953 = 10;
}
```

GIMPLE: Use of Pointers

Notes

GIMPLE: Use of Structures

test.c

```
typedef struct address
{ char *name;
} addr;

typedef struct student
{ int roll;
  addr *city;
} stud;

int main()
{ stud *s;

  s = malloc(sizeof(stud));
  s->roll = 1;
  s->city=malloc(sizeof(addr));
  s->city->name = "Mumbai";
}
```

test.c.004t.gimple

```
main ()
{
 void * D.2052;
 void * D.2053;
 struct addr * D.2054;
 struct addr * D.2055;
 struct stud * s;

 D.2052 = malloc (8);
 s = (struct stud *) D.2052;
 s->roll = 1;
 D.2053 = malloc (4);
 D.2054 = (struct addr *) D.2053;
 s->city = D.2054;
 D.2055 = s->city;
 D.2055->name = &"Mumbai"[0];
}
```

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GIMPLE: Use of Structures

Notes

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GIMPLE: Pointer to Array

test.c

```
int main()
{
  int *p_a, a[3];

  p_a = &a[0];

  *p_a = 10;
  *(p_a+1) = 20;
  *(p_a+2) = 30;
}
```

test.c.004t.gimple

```
main ()
{
  int * D.2048;
  int * D.2049;
  int * p_a;
  int a[3];

  p_a = &a[0];
  *p_a = 10;
  D.2048 = p_a + 4;
  *D.2048 = 20;
  D.2049 = p_a + 8;
  *D.2049 = 30;
}
```

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GIMPLE: Pointer to Array

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GIMPLE: Translation of Conditional Statements

test.c

```
int main()
{
    int a=2, b=3, c=4;
    while (a<=7)
    {
        a = a+1;
    }
     if (a<=12)
          a = a+b+c;

}
```

test.c.004t.gimple

```
if (a <= 12) goto <D.1200>;
else  goto <D.1201>;
<D.1200>:
D.1199 = a + b;
a = D.1199 + c;
<D.1201>:
```

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GIMPLE: Translation of Conditional Statements

Notes

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GIMPLE: Translation of Loops

test.c

```
int main()
{
    int a=2, b=3, c=4;
     while (a<=7)
     {
          a = a+1;
     }
    if (a<=12)
        a = a+b+c;
}
```

test.c.004t.gimple

```
goto <D.1197>;
<D.1196>:
a = a + 1;
<D.1197>:
if (a <= 7) goto <D.1196>;
else goto <D.1198>;
<D.1198>:
```

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GIMPLE: Translation of Loops

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GIMPLE: Translation of Loops

test.c

```
int main()
{
    int a=2, b=3, c=4;
     while (a<=7)
     {
          a = a+1;
     }
    if (a<=12)
        a = a+b+c;
}
```

test.c.004t.gimple

```
goto <D.1197>;
<D.1196>:
a = a + 1;
<D.1197>:
if (a <= 7) goto <D.1196>;
else goto <D.1198>;
<D.1198>:
```

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GIMPLE: Translation of Loops

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Control Flow Graph: Textual View

test.c.004t.gimple

```
if (a <= 12) goto <D.1200>;
else  goto <D.1201>;
<D.1200>:
D.1199 = a + b;
a = D.1199 + c;
<D.1201>:
```

test.c.012t.cfg

```
<bb 5>:
  if (a <= 12)
    goto <bb 6>;
  else
    goto <bb 7>;

<bb 6>:
  D.1199 = a + b;
  a = D.1199 + c;

<bb 7>:
  return;
```

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Control Flow Graph: Textual View

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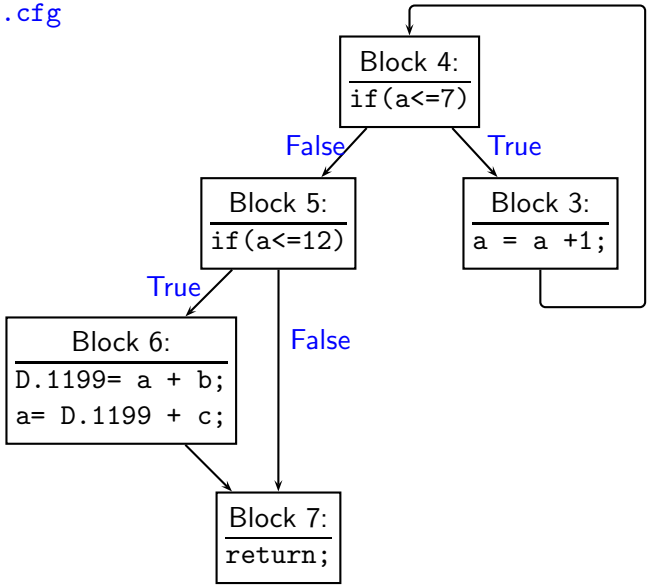
Control Flow Graph: Pictorial View

test.c.012t.cfg



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Control Flow Graph: Pictorial View

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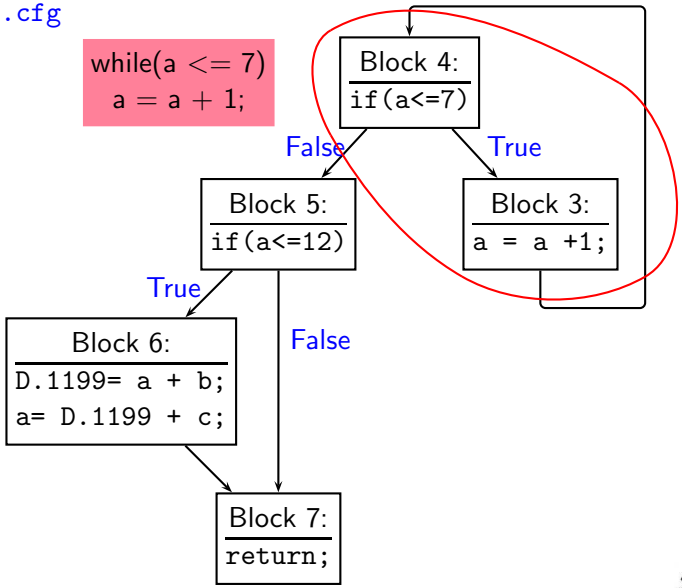
Control Flow Graph: Pictorial View

test.c.012t.cfg



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Control Flow Graph: Pictorial View

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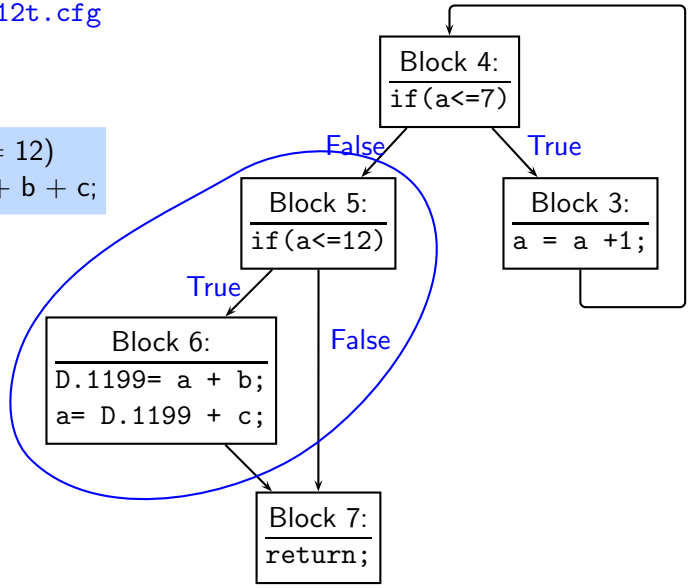
Control Flow Graph: Pictorial View

test.c.012t.cfg

if(a <= 12)
a = a + b + c;



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Control Flow Graph: Pictorial View

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GIMPLE: Function Calls and Call Graph

test.c

```
extern int divide(int, int);
int multiply(int a, int b)
{
   return a*b;
}

int main()
{ int x,y;
  x = divide(20,5);
  y = multiply(x,2);
  printf("%d\n", y);
}
```

test.c.000i.cgraph

```
printf/3(-1)  @0xb73c7ac8 availability:not_availa
  called by: main/1  (1.00 per call)
  calls:
divide/2(-1)  @0xb73c7a10 availability:not_availa
  called by: main/1  (1.00 per call)
  calls:
main/1(1)  @0xb73c7958 availability:available 38
  called by:
  calls: printf/3  (1.00 per call)
         multiply/0 (1.00 per call)
         divide/2 (1.00 per call)
multiply/0(0)  @0xb73c78a0 vailability:available
  called by: main/1  (1.00 per call)
  calls:
```


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GIMPLE: Function Calls and Call Graph

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GIMPLE: Function Calls and Call Graph

test.c

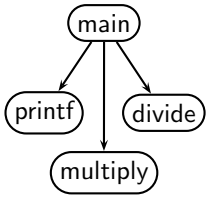
```
extern int divide(int, int);
int multiply(int a, int b)
{
   return a*b;
}

int main()
{ int x,y;
  x = divide(20,5);
  y = multiply(x,2);
  printf("%d\n", y);
}
```

test.c.000i.cgraph

```
printf/3(-1)
  called by: main/1
  calls:
divide/2(-1)
  called by: main/1
  calls:
main/1(1)
  called by:
  calls: printf/3
         multiply/0
         divide/2
multiply/0(0)
  called by: main/1
  calls:
```

call graph



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GIMPLE: Function Calls and Call Graph

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GIMPLE: Call Graphs for Recursive Functions

test.c

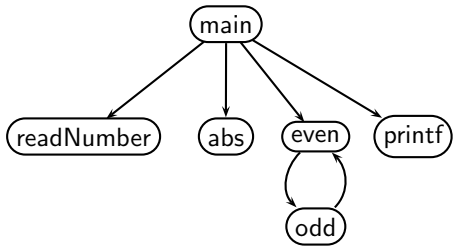
```
int even(int n)
{  if (n == 0) return 1;
   else return (!odd(n-1));
}

int odd(int n)
{  if (n == 1) return 1;
   else return (!even(n-1));
}

main()
{ int n;

  n = abs(readNumber());
  if (even(n))
    printf ("n is even\n");
  else printf ("n is odd\n");
}
```

call graph



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GIMPLE: Call Graphs for Recursive Functions

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Inspect GIMPLE When in Doubt

```
int x=2,y=3;
x = y++ + ++x + ++y;
```

What are the values of x and y?
x = 10 , y =5

x	3
y	3
$(y+x)$	6
$(y+x)+y$	

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Inspect GIMPLE When in Doubt

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Inspect GIMPLE When in Doubt


```
int x=2,y=3;
x = y++ + ++x + ++y;
```

What are the values of x and y?
x = 10 , y =5

x	3
y	4
$(y+x)$	6
$(y+x)+y$	

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Inspect GIMPLE When in Doubt

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Inspect GIMPLE When in Doubt

```
int x=2,y=3;
x = y++ + ++x + ++y;
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What are the values of x and y?
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x	3
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$(y+x)+y$	

Notes

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Inspect GIMPLE When in Doubt

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Inspect GIMPLE When in Doubt


```
int x=2,y=3;
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```

What are the values of x and y?
x = 10 , y =5

x	3
y	5
$(y+x)$	6
$(y+x)+y$	11

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Inspect GIMPLE When in Doubt

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Inspect GIMPLE When in Doubt

```
int x=2,y=3;
x = y++ + ++x + ++y;
```

What are the values of x and y?

x = 10 , y =5

x	3
y	5
$(y + x)$	6
$(y + x) + y$	11

```
x = 2;
y = 3;
x = x + 1; /* 3 */
D.1572 = y + x;  /* 6 */
y = y + 1;  /* 4 */
x = D.1572 + y;  /* 10 */
y = y + 1;  /* 5 */
```

Notes

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Inspect GIMPLE When in Doubt

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Part 3

Examining RTL Dumps

Notes

RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.141r.expand`

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
        (plus:SI
           (mem/c/i:SI
              (plus:SI
                 (reg/f:SI 54 virtual-stack-vars)
                 (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

Notes

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RTL for i386: Arithmetic Operations (1)

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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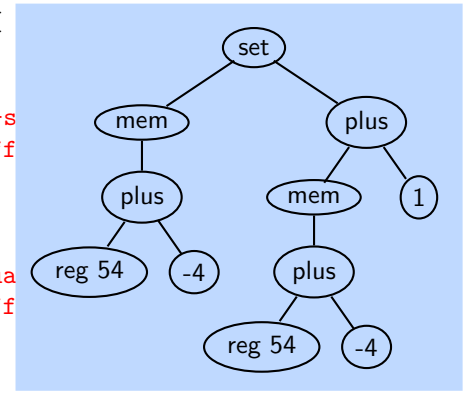
RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.141r.expand`

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-s
             (const_int -4 [0xfffff
        (plus:SI
           (mem/c/i:SI
              (plus:SI
                 (reg/f:SI 54 virtua
                 (const_int -4 [0xff
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```



Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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RTL for i386: Arithmetic Operations (1)

Notes

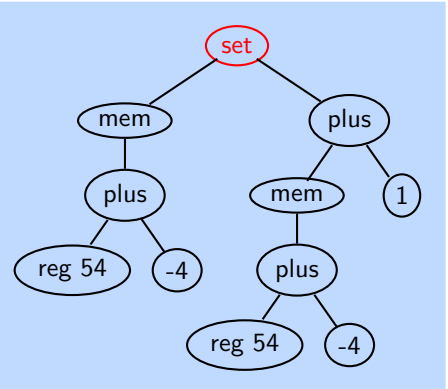
Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.141r.expand`

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-s
             (const_int -4 [0xfffff
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtua
                (const_int -4 [0xff
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))
```



Notes

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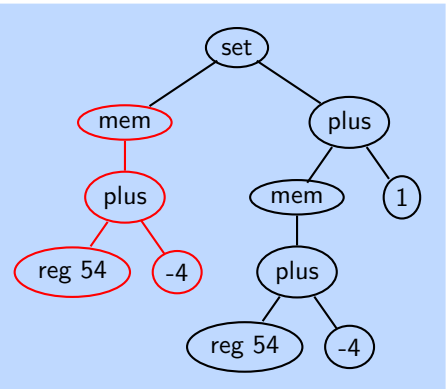
RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.141r.expand`

a is a local variable allocated on stack


```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-s
             (const_int -4 [0xfffff
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtua
                (const_int -4 [0xff
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))
```

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Notes

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RTL for i386: Arithmetic Operations (1)

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

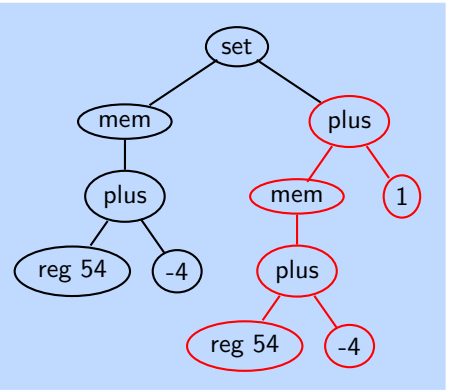
RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.141r.expand`

a is a local variable allocated on stack

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-s
             (const_int -4 [0xfffff
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtua
                (const_int -4 [0xff
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```



Notes

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RTL for i386: Arithmetic Operations (1)

Notes

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July 2010 Graybox Probing-I: Examining RTL Dumps 29/43

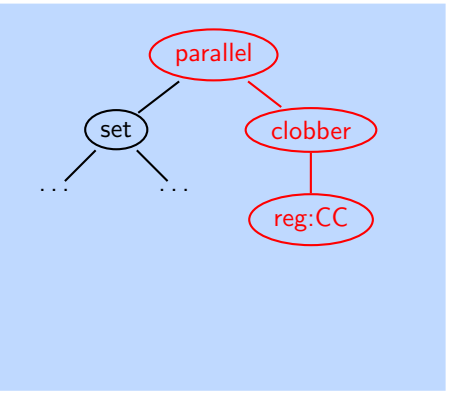
RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.141r.expand`

side-effect of plus may modify condition code register non-deterministically

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-s
             (const_int -4 [0xfffff
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtua
                (const_int -4 [0xff
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```



Notes

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RTL for i386: Arithmetic Operations (1)

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.141r.c`

```
(insn 12 11 13 4 t.c:24 (p
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

Output with `slim` suffix

```
{[r54:SI-0x4]=[r54:SI-0x4]+0x1;
   clobber flags:CC;
}
```


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RTL for i386: Arithmetic Operations (1)

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

Current Instruction

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Additional Information in RTL

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

Previous Instruction

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

Next Instruction

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

Basic Block

Notes

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Additional Information in RTL

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Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
       (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

File name: Line number

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Notes

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Additional Information in RTL

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
        (plus:SI
           (mem/c/i:SI
              (plus:SI
                 (reg/f:SI 54 virtual-stack-vars)
                 (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

memory reference that does not trap

Notes

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Additional Information in RTL

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Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
        (plus:SI
           (mem/c/i:SI
              (plus:SI
                 (reg/f:SI 54 virtual-stack-vars)
                 (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

scalar that is not a part of an aggregate

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Notes

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Additional Information in RTL

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
        (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

register that holds a pointer

Notes

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Additional Information in RTL

Notes

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Additional Information in RTL

```
(insn 12 11 13 4 t.c:24 (parallel [
   (set (mem/c/i:SI
          (plus:SI
             (reg/f:SI 54 virtual-stack-vars)
             (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
        (plus:SI
          (mem/c/i:SI
             (plus:SI
                (reg/f:SI 54 virtual-stack-vars)
                (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
          (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

single integer

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Additional Information in RTL

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for i386: Arithmetic Operations (2)

Translation of $a = a + 1$ when a is a global variable

Dump file: `test.c.141r.expand`

```
(insn 11 10 12 4 t.c:26 (set
   (reg:SI 64 [ a.0 ])
   (mem/c/i:SI
      (symbol_ref:SI ("a")  <var_decl 0xb7d8d000 a>) [0 a+0 S4 A32])) -1 (nil))

(insn 12 11 13 4 t.c:26 (parallel [
   (set (reg:SI 63 [ a.1 ])
        (plus:SI
           (reg:SI 64 [ a.0 ])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))

(insn 13 12 14 4 t.c:26 (set
   (mem/c/i:SI (symbol_ref:SI ("a")  <var_decl 0xb7d8d000 a>) [0 a+0 S4 A32])
   (reg:SI 63 [ a.1 ])) -1 (nil))
```


Notes

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RTL for i386: Arithmetic Operations (2)

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RTL for i386: Arithmetic Operations (2)

Translation of $a = a + 1$ when a is a global variable

Dump file: `test.c.141r.expand`

```
(insn 11 10 12 4 t.c:26 (set
   (reg:SI 64 [ a.0 ])
   (mem/c/i:SI
      (symbol_ref:SI ("a")  <var_decl 0
```

Load a into reg64

```
(insn 12 11 13 4 t.c:26 (parallel [
   (set (reg:SI 63 [ a.1 ])
        (plus:SI
           (reg:SI 64 [ a.0 ])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))

(insn 13 12 14 4 t.c:26 (set
   (mem/c/i:SI (symbol_ref:SI ("a")  <var_decl 0xb7d8d000 a>) [0 a+0 S4 A32])
   (reg:SI 63 [ a.1 ])) -1 (nil))
```

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RTL for i386: Arithmetic Operations (2)

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for i386: Arithmetic Operations (2)

Translation of $a = a + 1$ when a is a global variable

Dump file: `test.c.141r.expand`

```
(insn 11 10 12 4 t.c:26 (set
   (reg:SI 64 [ a.0 ])
   (mem/c/i:SI
      (symbol_ref:SI ("a")  <var_decl 0
                                        2])) -1 (nil))

(insn 12 11 13 4 t.c:26 (parallel [
   (set (reg:SI 63 [ a.1 ])
        (plus:SI
           (reg:SI 64 [ a.0 ])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))

(insn 13 12 14 4 t.c:26 (set
   (mem/c/i:SI (symbol_ref:SI ("a")  <var_decl 0xb7d8d000 a>) [0 a+0 S4 A32])
   (reg:SI 63 [ a.1 ])) -1 (nil))
```

Load a into reg64

reg63 = reg64 + 1

Notes

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RTL for i386: Arithmetic Operations (2)

Notes

July 2010 Graybox Probing-I: Examining RTL Dumps 31/43

RTL for i386: Arithmetic Operations (2)

Translation of $a = a + 1$ when a is a global variable

Dump file: `test.c.141r.expand`

```
(insn 11 10 12 4 t.c:26 (set
   (reg:SI 64 [ a.0 ])
   (mem/c/i:SI
      (symbol_ref:SI ("a")  <var_decl 0
                                        2])) -1 (nil))

(insn 12 11 13 4 t.c:26 (parallel [
   (set (reg:SI 63 [ a.1 ])
        (plus:SI
           (reg:SI 64 [ a.0 ])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))

(insn 13 12 14 4 t.c:26 (set
   (mem/c/i:SI (symbol_ref:SI ("a")  <var_decl 0xb7d8d000 a>) [0 a+0 S4 A32])
   (reg:SI 63 [ a.1 ])) -1 (nil))
```

Load a into reg64

reg63 = reg64 + 1

store reg63 into a

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for i386: Arithmetic Operations (2)

Translation of $a = a + 1$ when a is a global variable

Dump file: `test.c.141r.expand`

```
(insn 11 10 12 4 t.c:26 (set
   (reg:SI 64 [ a.0 ])
   (mem/c/i:SI
      (symbol_ref:SI ("a")  <var_decl 0
                                        2])) -1 (nil))

(insn 12 11 13 4 t.c:26 (parallel [
   (set (reg:SI 63 [ a.1 ])
        (plus:SI
           (reg:SI 64 [ a.0 ])
           (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
 ]) -1 (nil))

(insn 13 12 14 4 t.c:26 (set
   (mem/c/i:SI (symbol_ref:SI ("a")  <var_decl 0xb7d8d000 a>) [0 a+0 S4 A32])
   (reg:SI 63 [ a.1 ])) -1 (nil))
```

Load a into reg64
reg63 = reg64 + 1
store reg63 into a

Output with slim suffix

```
r64:SI=['a']
{r63:SI=r64:SI+0x1;
   clobber flags:CC;
}
['a']=r63:SI
```

Notes

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RTL for i386: Arithmetic Operations (2)
Notes
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RTL for i386: Arithmetic Operations (3)

Translation of $a = a + 1$ when a is a formal parameter

Dump file: `test.c.141r.expand`

```
(insn 10 9 11 4 t1.c:25 (parallel [
   (set
      (mem/c/i:SI
         (reg/f:SI 53 virtual-incoming-args) [0 a+0 S4 A32])
      (plus:SI
         (mem/c/i:SI
            (reg/f:SI 53 virtual-incoming-args) [0 a+0 S4 A32])
            (const_int 1 [0x1])))
    (clobber (reg:CC 17 flags))
  ]) -1 (nil))
```

Notes

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RTL for i386: Arithmetic Operations (3)
Notes
Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for i386: Arithmetic Operations (3)

Translation of $a = a + 1$ when a is a formal parameter

Dump file: `test.c.141r.expand`

```
(insn 10 9 11 4 t1.c:25 (parallel [
   (set
      (mem/c/i:SI
         (reg/f:SI 53 virtual-incoming-
      (plus:SI
         (mem/c/i:SI
            (reg/f:SI 53 virtual-incomi
               (const_int 1 [0x1])))
    (clobber (reg:CC 17 flags))
 ]) -1 (nil))
```

Access through argument pointer register instead of frame pointer register

No offset required?

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RTL for i386: Arithmetic Operations (3)

Notes

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RTL for i386: Arithmetic Operations (3)

Translation of $a = a + 1$ when a is a formal parameter

Dump file: `test.c.141r.expand`

```
(insn 10 9 11 4 t1.c:25 (parallel [
   (set
      (mem/c/i:SI
         (reg/f:SI 53 virtual-incoming-
      (plus:SI
         (mem/c/i:SI
            (reg/f:SI 53 virtual-incomi
               (const_int 1 [0x1])))
    (clobber (reg:CC 17 flags))
 ]) -1 (nil))
```

Access through argument pointer register instead of frame pointer register

No offset required?

Output with `slim` suffix

```
{[r53:SI]=[r53:SI]+0x1;
clobber flags:CC;
}
```

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RTL for i386: Arithmetic Operations (3)

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for i386: Arithmetic Operation (4)

Translation of $a = a + 1$ when a is the second formal parameter

Dump file: `test.c.141r.expand`

```
(insn 10 9 11 4 t1.c:25 (parallel [
   (set
      (mem/c/i:SI
         (plus:SI
            (reg/f:SI 53 virtual-incoming-args)
            (const_int 4 [0x4])) [0 a+0 S4 A32])
      (plus:SI
         (mem/c/i:SI
            (plus:SI
               (reg/f:SI 53 virtual-incoming-args)
               (const_int 4 [0x4])) [0 a+0 S4 A32])
         (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))
```


Notes

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RTL for i386: Arithmetic Operation (4)

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RTL for i386: Arithmetic Operation (4)

Translation of $a = a + 1$ when a is the second formal parameter

Dump file: `test.c.141r.expand`

```
(insn 10 9 11 4 t1.c:25 (parallel
   (set
      (mem/c/i:SI
         (plus:SI
            (reg/f:SI 53 virtual-
            (const_int 4 [0x4]))
      (plus:SI
         (mem/c/i:SI
            (plus:SI
               (reg/f:SI 53 virtu
               (const_int 4 [0x4]
         (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))
```

Offset 4 added to the argument pointer register

When a is the first parameter, its offset is 0!

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Notes

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RTL for i386: Arithmetic Operation (4)

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RTL for i386: Arithmetic Operation (4)

Translation of $a = a + 1$ when a is the second formal parameter

Dump file: `test.c.141r.expand`

```
(insn 10 9 11 4 t1.c:25 (parallel
   (set
      (mem/c/i:SI
         (plus:SI
            (reg/f:SI 53 virtual-
            (const_int 4 [0x4]))
      (plus:SI
         (mem/c/i:SI
            (plus:SI
               (reg/f:SI 53 virtu
               (const_int 4 [0x4]
         (const_int 1 [0x1])))
   (clobber (reg:CC 17 flags))
]) -1 (nil))
```

Offset 4 added to the argument pointer register

When a is the first parameter, its offset is 0!

Output with `slim` suffix

```
{[r53:SI+0x4]=[r53:SI+0x4]+0x1;
 clobber flags:CC;
}
```


RTL for i386: Arithmetic Operation (4)

Notes

RTL for spim: Arithmetic Operations

Translation of $a = a + 1$ when a is a local variable

Dump file: `test.c.141r.expand`

r39=stack($fp - 4)
r40=r39+1
stack($fp - 4)=r40

```
(insn 7 6 8 4 test.c:6 (set (reg:SI 39)
      (mem/c/i:SI (plus:SI (reg/f:SI 33 virtual-stack-vars)
            (const_int -4 [...])) [...])) -1 (nil))
(insn 8 7 9 4 test.c:6 (set (reg:SI 40)
      (plus:SI (reg:SI 39)
           (const_int 1 [...]))) -1 (nil))
(insn 9 8 10 4 test.c:6 (set
      (mem/c/i:SI (plus:SI (reg/f:SI 33 virtual-stack-vars)
           (const_int -4 [...])) [...])
      (reg:SI 40)) -1 (nil))
```

In spim, a variable is loaded into register to perform any instruction, hence three instructions are generated

RTL for spim: Arithmetic Operations

Notes

RTL for i386: Control Flow

What does this represent?

```
(jump_insn 15 14 16 4 p1.c:6 (set (pc)
     (if_then_else (lt (reg:CCGC 17 flags)
         (const_int 0 [0x0]))
       (label_ref 12)
       (pc))) (nil)
     (nil))
```

pc = r17 <0 ? label(12) : pc

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RTL for i386: Control Flow

Notes

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RTL for i386: Control Flow

Translation of `if (a > b) { /* something */ }`

Dump file: `test.c.141r.expand`

```
(insn 8 7 9 test.c:7 (set (reg:SI 61)
   (mem/c/i:SI (plus:SI (reg/f:SI 54 virtual-stack-vars)
   (const_int -8 [0xfffffff8])) [0 a+0 S4 A32])) -1 (nil))
(insn 9 8 10 test.c:7 (set (reg:CCGC 17 flags)
   (compare:CCGC (reg:SI 61)
      (mem/c/i:SI (plus:SI (reg/f:SI 54 virtual-stack-vars)
      (const_int -4 [0xfffffffc])) [0 b+0 S4 A32]))) -1 (nil))
(jump_insn 10 9 0 test.c:7 (set (pc)
    (if_then_else (le (reg:CCGC 17 flags)
        (const_int 0 [0x0]))
        (label_ref 0)
        (pc))) -1 (nil))
```

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RTL for i386: Control Flow

Notes

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Observing Register Allocation for i386

test.c

```
int main()
{
   int a=2, b=3;
   if(a<=12)
     a = a * b;
}
```

test.c.185r.asmcons

(observable dump before register allocation)

```
(insn 10 9 11 3 test.c:5 (set (reg:SI 59)
  (mem/c/i:SI (plus:SI (reg/f:SI 20 frame)
     (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])) 44 *movs

(insn 11 10 12 3 test.c:5 (parallel [
  (set (reg:SI 60)
     (mult:SI (reg:SI 59)
        (mem/c/i:SI (plus:SI (reg/f:SI 20 frame)
           (const_int -8 [0xfffffff8])) [0 b+0 S4 A32])))
  (clobber (reg:CC 17 flags))
  ]) 262 *mulsi3_1 (nil))

(insn 12 11 22 3 test.c:5 (set
      (mem/c/i:SI (plus:SI (reg/f:SI 20 frame)
        (const_int -4 [0xfffffffc])) [0 a+0 S4 A32])
        (reg:SI 60)) 44 *movsi_1 (nil))
```

Notes

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Observing Register Allocation for i386

Notes

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Observing Register Allocation for i386

test.c.185r.asmcons

```
(set (reg:SI 59) (mem/c/i:SI
   (plus:SI
     (reg/f:SI 20 frame)
     (const_int -4))))

(set (reg:SI 60)
  (mult:SI
     (reg:SI 59)
     (mem/c/i:SI
       (plus:SI
         (reg/f:SI 20 frame)
         (const_int -8)) )))

(set (mem/c/i:SI (plus:SI
      (reg/f:SI 20 frame)
       (const_int -4)))
   (reg:SI 60))
```

test.c.188r.ira

```
(set (reg:SI 0 ax [59]) (mem/c/i:SI
   (plus:SI
     (reg/f:SI 6 bp)
     (const_int -4))))

(set (reg:SI 0 ax [60])
  (mult:SI
     (reg:SI 0 ax [59])
     (mem/c/i:SI
       (plus:SI
         (reg/f:SI 6 bp)
         (const_int -8)) )))

(set (mem/c/i:SI (plus:SI
      (reg/f:SI 6 bp)
       (const_int -4)))
   (reg:SI 0 ax [60]))
```


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Observing Register Allocation for i386

Notes

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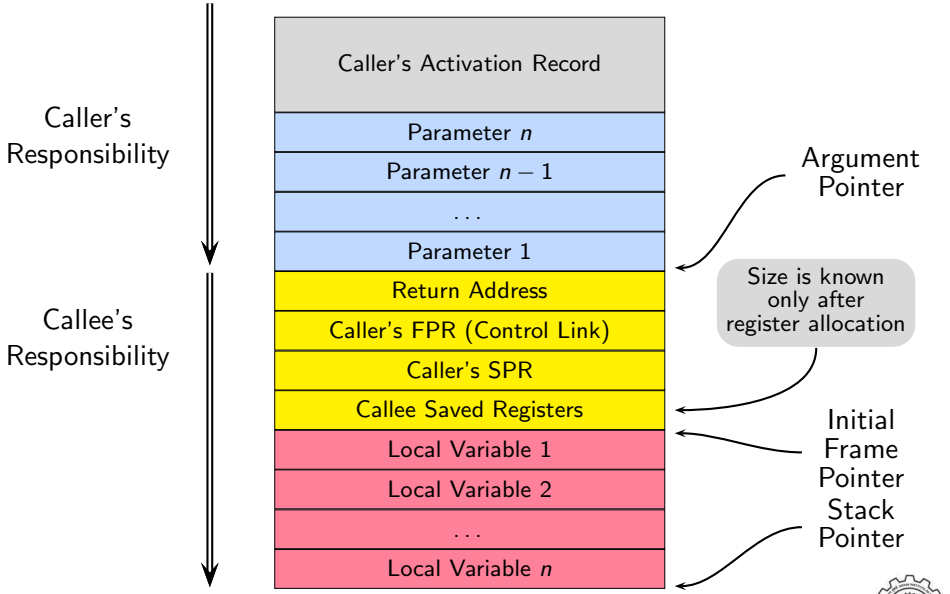
Activation Record Structure in Spim



Activation Record Structure in Spim

Notes

RTL for Function Calls in spim

Calling function	Called function
• Allocate memory for actual parameters on stack • Copy actual parameters • **Call function** • Get result from stack (pop) • Deallocate memory for activation record (pop)	• Allocate memory for return value (push) • Store mandatory callee save registers (push) • Set frame pointer • Allocate local variables (push) • **Execute code** • Put result in return value space • Deallocate local variables (pop) • Load callee save registers (pop) • Return

RTL for Function Calls in spim

Notes

Prologue and Epilogue: spim

Dump file: `test.c.193r.pro_and_epilogue`

```
(insn 17 3 18 2 test.c:2
   (set (mem:SI (reg/f:SI 29 $sp) [0 S4 A8])
        (reg:SI 31 $ra)) -1 (nil))
(insn 18 17 19 2 test.c:2
   (set (mem:SI (plus:SI (reg/f:SI 29 $sp)
                   (const_int -4 [...])) [...])
      (reg/f:SI 29 $sp)) -1 (nil))
(insn 19 18 20 2 test.c:2 (set
      (mem:SI (plus:SI (reg/f:SI 29 $sp)
                  (const_int -8 [...])) [...])
      (reg/f:SI 30 $fp)) -1 (nil))
(insn 20 19 21 2 test.c:2 (set (reg/f:SI 30 $fp)
       (reg/f:SI 29 $sp)) -1 (nil))
(insn 21 20 22 2 test.c:2 (set (reg/f:SI 29 $sp)
    (plus:SI (reg/f:SI 30 $fp)
            (const_int -32 [...]))) -1 (nil))
```

```
sw $ra, 0($sp)
sw $sp, 4($sp)
sw $fp, 8($sp)
move $fp,$sp
addi $sp,$fp,32
```


Notes

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Prologue and Epilogue: spim

Notes

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Part 4

Examining Assembly Dumps

Notes

i386 Assembly

Dump file: `test.s`

```
        jmp   .L2
.L3:
        addl  $1, -4(%ebp)
.L2:
        cmpl  $7, -4(%ebp)
        jle   .L3
        cmpl  $12, -4(%ebp)
        jg    .L6
        movl  -8(%ebp), %edx
        movl  -4(%ebp), %eax
        leal  (%edx,%eax), %eax
        addl  -12(%ebp), %eax
        movl  %eax, -4(%ebp)
.L6:
```

```
while (a <= 7)
{
    a = a+1;
}
if (a <= 12)
{
    a = a+b+c;
}
```

Notes

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i386 Assembly

Notes

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i386 Assembly

Dump file: test.s

```
        jmp   .L2
.L3:
        addl  $1, -4(%ebp)
.L2:
        cmpl  $7, -4(%ebp)
        jle   .L3
        cmpl  $12, -4(%ebp)
        jg    .L6
        movl  -8(%ebp), %edx
        movl  -4(%ebp), %eax
        leal  (%edx,%eax), %eax
        addl  -12(%ebp), %eax
        movl  %eax, -4(%ebp)
.L6:
```

```
while (a <= 7)
{
    a = a+1;
}
if (a <= 12)
{
    a = a+b+c;
}
```

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Notes

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i386 Assembly

Notes

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i386 Assembly

Dump file: `test.s`

```
        jmp   .L2
.L3:
        addl  $1, -4(%ebp)
.L2:
        cmpl  $7, -4(%ebp)
        jle   .L3
        cmpl  $12, -4(%ebp)
        jg    .L6
        movl  -8(%ebp), %edx
        movl  -4(%ebp), %eax
        leal  (%edx,%eax), %eax
        addl  -12(%ebp), %eax
        movl  %eax, -4(%ebp)
.L6:
```

```
while (a <= 7)
{
    a = a+1;
}
if (a <= 12)
{
    a = a+b+c;
}
```

Notes

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i386 Assembly

Dump file: test.s

jmp .L2
.L3:
addl $1, -4(%ebp)
.L2:
cmpl $7, -4(%ebp)
jle .L3
cmpl $12, -4(%ebp)
jg .L6
movl -8(%ebp), %edx
movl -4(%ebp), %eax
leal (%edx,%eax), %eax
addl -12(%ebp), %eax
movl %eax, -4(%ebp)
.L6:

while (a <= 7)
{
a = a+1;
}
if (a <= 12)
{
a = a+b+c;
}

Notes

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i386 Assembly

Dump file: test.s

jmp .L2
.L3:
addl $1, -4(%ebp)
.L2:
cmpl $7, -4(%ebp)
jle .L3
cmpl $12, -4(%ebp)
jg .L6
movl -8(%ebp), %edx
movl -4(%ebp), %eax
leal (%edx,%eax), %eax
addl -12(%ebp), %eax
movl %eax, -4(%ebp)
.L6:

while (a <= 7)
{
a = a+1;
}
if (a <= 12)
{
a = a+b+c;
}

Notes

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Part 5

Conclusions

Notes

Gray Box Probing of GCC: Conclusions

- Source code is transformed into assembly by lowering the abstraction level step by step to bring it close to machine architecture
- This transformation can be understood to a large extent by observing inputs and output of the different steps in the transformation
- In gcc, the output of almost all the passes can be examined
- The complete list of dumps can be figured out by the command

```
man gcc
```

Notes

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Gray Box Probing of GCC: Conclusions

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay