Workshop on Essential Abstractions in GCC

First Level Gray Box Probing

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

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1 July 2011

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

What is Gray Box Probing of GCC?

Notes

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

Notes

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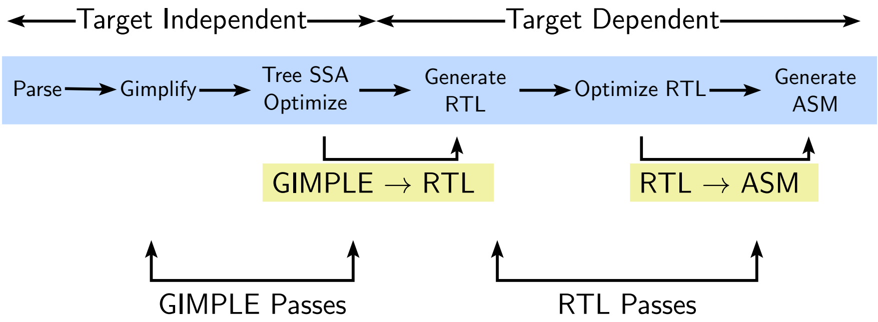
Basic Transformations in GCC

Tranformation from a language to a *different* language



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Basic Transformations in GCC

Notes

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Transformation Passes in GCC 4.6.0

- A total of 207 unique pass names initialized in `${SOURCE}/gcc/passes.c`
  Total number of passes is 241.
  - 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

Transformation Passes in GCC 4.6.0

Notes

Passes On GIMPLE in GCC 4.6.0

Pass Group	Examples	Number of passes
Lowering	GIMPLE IR, CFG Construction	10
Simple Interprocedural Passes (Non-LTO)	Conditional Constant Propagation, Inlining, SSA Construction	38
Regular Interprocedural Passes (LTO)	Constant Propagation, Inlining, Pointer Analysis	10
LTO generation passes		02
Other Intraprocedural Optimizations	Constant Propagation, Dead Code Elimination, PRE Value Range Propagation, Rename SSA	65
Loop Optimizations	Vectorization, Parallelization, Copy Propagation, Dead Code Elimination	28
Generating RTL		01
Total number of passes on GIMPLE		154

Passes On GIMPLE in GCC 4.6.0

Notes

Passes On RTL in GCC 4.6.0

Pass Group	Examples	Number of passes
Intraprocedural Optimizations	CSE, Jump Optimization, Dead Code Elimination, Jump Optimization	27
Loop Optimizations	Loop Invariant Movement, Peeling, Unswitching	07
Machine Dependent Optimizations	Register Allocation, Instruction Scheduling, Peephole Optimizations	50
Assembly Emission and Finishing		03
Total number of passes on RTL		87

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Passes On RTL in GCC 4.6.0

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

Notes

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

Notes

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Total Number of Dumps

Optimization Level	Number of Dumps	Goals
Default	47	Fast compilation
O1	134	
O2	158	
O3	168	
Os	156	Optimize for space

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Total Number of Dumps

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Selected Dumps for Our Example Program

GIMPLE dumps (t)

- 001t.tu
- 003t.original
- 004t.gimple
- 006t.vcg
- 009t.omplower
- 010t.lower
- 012t.eh
- 013t.cfg
- 017t.ssa
- 018t.veclower
- 019t.inline_param1
- 020t.einline
- 037t.release_ssa
- 038t.inline_param2
- 044i.whole-program
- 048i.inline
- 138t.cplxlower0
- 143t.optimized
- 224t.statistics

ipa dumps (i)

- 000i.cgraph
- 014i.visibility
- 015i.early_local_cleanups
- 044i.whole-program
- 048i.inline

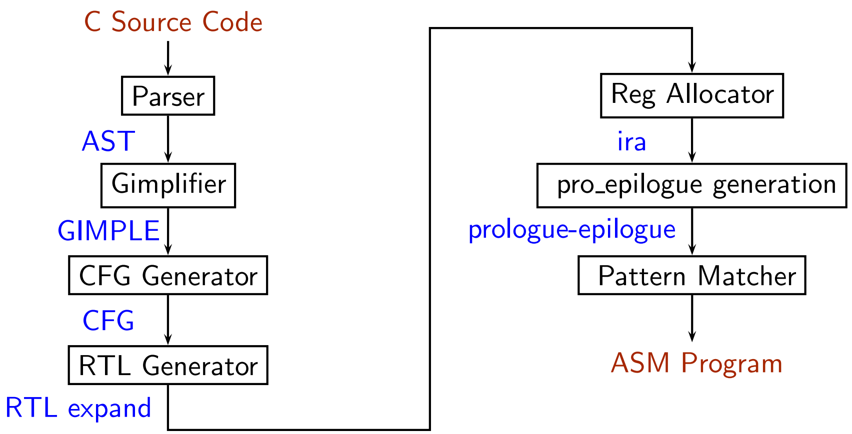
rtl dumps (r)

- 144r.expand
- 145r.sibling
- 147r.initvals
- 148r.unshare
- 149r.vregs
- 150r.into_cfglayout
- 151r.jump
- 163r.reginfo
- 183r.outof_cfglayout
- 184r.split1
- 186r.dfinit
- 187r.mode_sw
- 188r.asmcons
- 191r.ira
- 194r.split2
- 198r.pro_and_epilogue
- 211r.stack
- 212r.alignments
- 215r.mach
- 216r.barriers
- 220r.shorten
- 221r.nothrow
- 222r.final
- 223r.dfinish
- assembly

Selected Dumps for Our Example Program

Notes

Passes for First Level Graybox Probing of GCC



Lowering of abstraction!

Passes for First Level Graybox Probing of GCC

Notes

Part 2

Examining GIMPLE Dumps

Notes

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

Gimplifier

Notes

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;
```

Global variables are treated as "memory locations" and local variables are treated as "registers"

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GIMPLE: Composite Expressions Involving Local and Global Variables

Notes

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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

Notes

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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;
```

- No notion of "addressable memory" in GIMPLE.
- Array reference is a single operation in GIMPLE and is linearized in RTL during expansion

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GIMPLE: 2-D Array Accesses

Notes

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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;
}
```


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GIMPLE: Use of Pointers

Notes

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GIMPLE: Use of Structures

test.c

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

typedef struct student
{ int roll;
  ad *ct;
} st;

int main()
{ st *s;
  s = malloc(sizeof(st));
  s->roll = 1;
  s->ct=malloc(sizeof(ad));
  s->ct->name = "Mumbai";
}
```

test.c.004t.gimple

```
main ()
{
  void * D.1957;
  struct ad * D.1958;
  struct st * s;
  extern void * malloc (unsigned int);

  s = malloc (8);
  s->roll = 1;
  D.1957 = malloc (4);
  s->ct = D.1957;
  D.1958 = s->ct;
  D.1958->name = "Mumbai";
}
```


GIMPLE: Use of Structures

Notes

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;
}
```


GIMPLE: Pointer to Array

Notes

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

Notes

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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.013t.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

Notes

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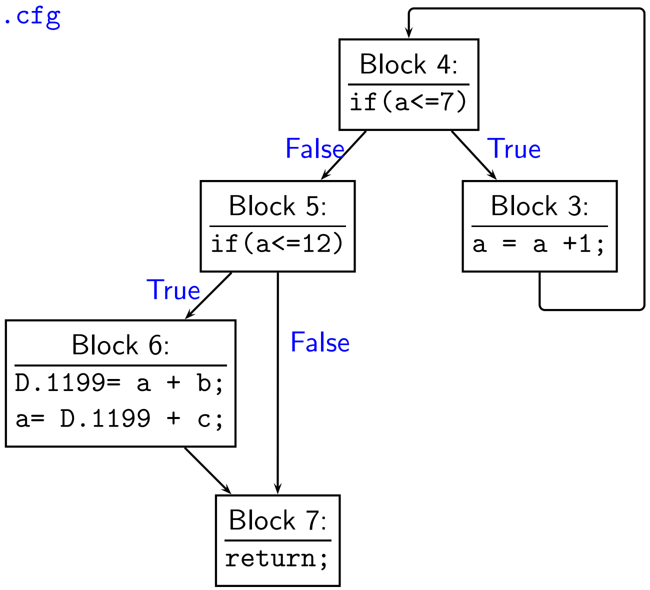
Control Flow Graph: Pictorial View

test.c.013t.cfg



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Control Flow Graph: Pictorial View

Notes

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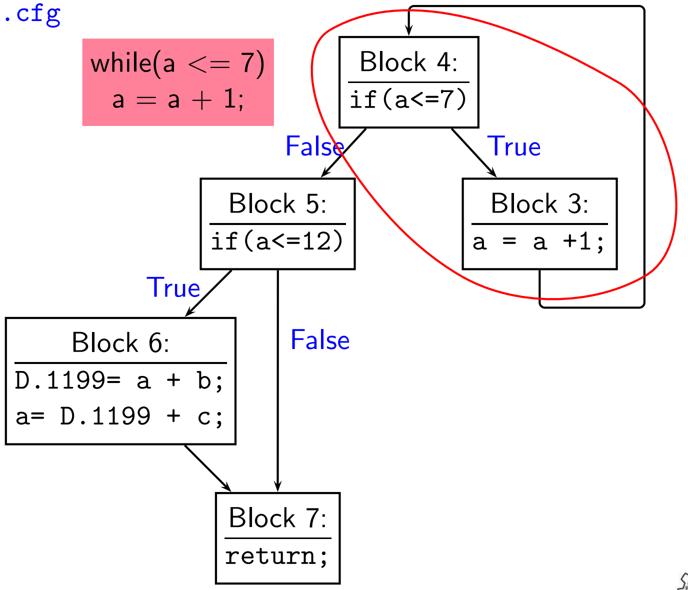
Control Flow Graph: Pictorial View

test.c.013t.cfg



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Control Flow Graph: Pictorial View

Notes

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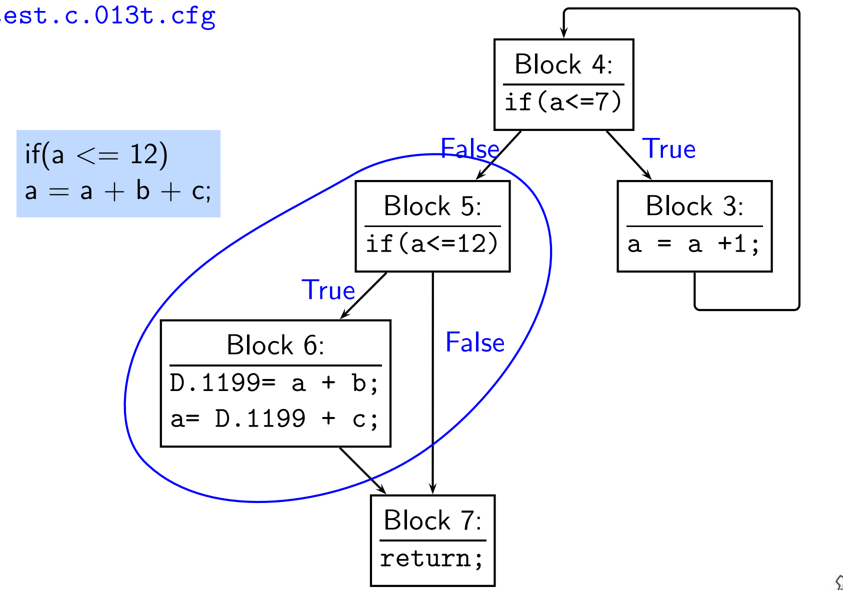
Control Flow Graph: Pictorial View

test.c.013t.cfg



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Control Flow Graph: Pictorial View

Notes

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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:
```

visible

visibl

GIMPLE: Function Calls and Call Graph

Notes

GIMPLE: Function Calls and Call Graph

test.c

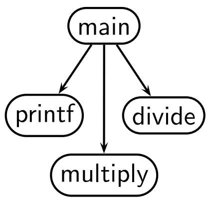
```
extern int divide(int, int);
int multiply(int a, int b)
{
   return a*b;
}

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



GIMPLE: Function Calls and Call Graph

Notes

GIMPLE: Call Graphs for Recursive Functions

test.c

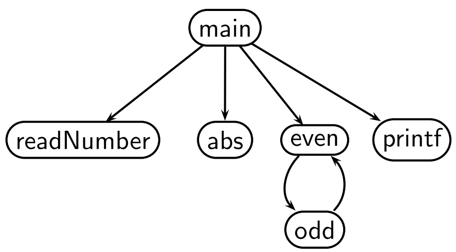
```
int even(int n)
{  if (n == 0) return 1;
   else return (!odd(n-1));
}

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

Notes

Inspect GIMPLE When in Doubt (1)

```
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 (1)

Notes

Inspect GIMPLE When in Doubt (1)

```
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
$(y+x)+y$	

Inspect GIMPLE When in Doubt (1)

Notes

Inspect GIMPLE When in Doubt (1)

```
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
$(y+x)+y$	

Inspect GIMPLE When in Doubt (1)

Notes

Inspect GIMPLE When in Doubt (1)

```
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

Inspect GIMPLE When in Doubt (1)

Notes

Inspect GIMPLE When in Doubt (1)

```
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 */
```


Inspect GIMPLE When in Doubt (1)

Notes

Inspect GIMPLE When in Doubt (2)

- How is `a[i] = i++` handled?
  This is an undefined behaviour as per C standards.
- What is the order of parameter evaluation?
  For a call `f(getX(),getY())`, is the order left to right? arbitrary?
  Is the evaluation order in GCC consistent?
- Understanding complicated declarations in C can be difficult
  What does the following declaration mean :

  ```
  int * (* (*MYVAR) (int) ) [10];
  ```

  Hint: Use `-fdump-tree-original-raw-verbose` option. The dump to see is `003t.original`

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Inspect GIMPLE When in Doubt (2)

Notes

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Part 3

Examining RTL Dumps

Notes

RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.144r.expand`

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```


RTL for i386: Arithmetic Operations (1)

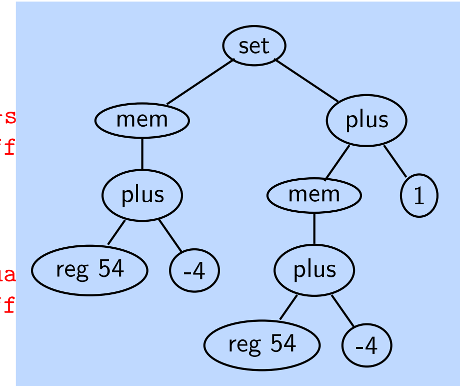
Notes

RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.144r.expand`

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```



RTL for i386: Arithmetic Operations (1)

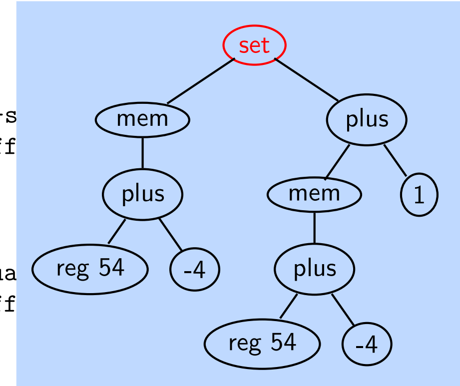
Notes

RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.144r.expand`

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```



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RTL for i386: Arithmetic Operations (1)

Notes

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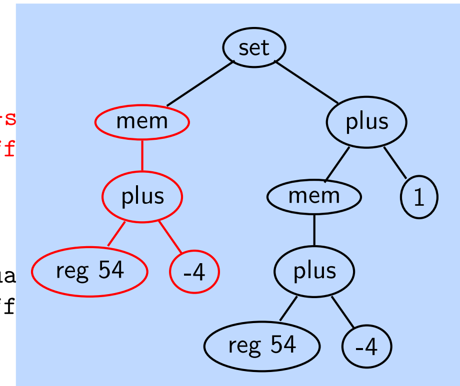
RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.144r.expand`

a is a local variable allocated on stack

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -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

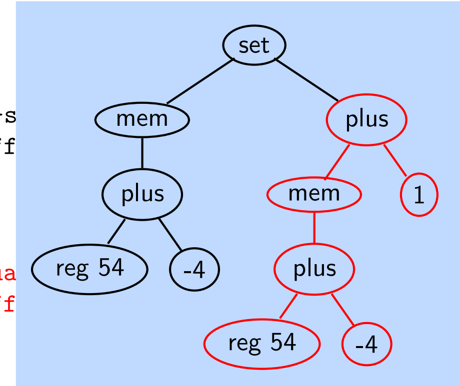
RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: test.c.144r.expand

a is a local variable allocated on stack

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```



RTL for i386: Arithmetic Operations (1)

Notes

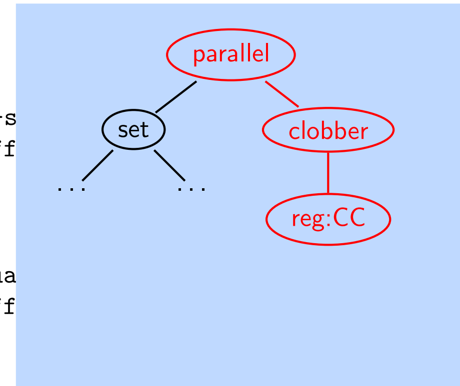
RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: test.c.144r.expand

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

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```



RTL for i386: Arithmetic Operations (1)

Notes

RTL for i386: Arithmetic Operations (1)

Translation of $a = a + 1$

Dump file: `test.c.144r.e`

Output with `slim` suffix

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

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```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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 (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))
  ]) t.c:24 -1 (nil))
```

Current Instruction (points to 12)

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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 (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))
  ]) t.c:24 -1 (nil))
```

Previous Instruction

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```

Next Instruction

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```

Basic Block

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```

File name: Line number

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```

memory reference that does not trap

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```

scalar that is not a part of an aggregate

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```

register that holds a pointer

Additional Information in RTL

Notes

Additional Information in RTL

```
(insn 12 11 13 4 (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))
  ]) t.c:24 -1 (nil))
```


single integer

Additional Information in RTL

Notes

RTL for i386: Arithmetic Operations (2)

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

Dump file: `test.c.144r.expand`

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

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

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


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RTL for i386: Arithmetic Operations (2)

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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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.144r.expand`

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

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

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

Load a into reg64

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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RTL for i386: Arithmetic Operations (2)

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.144r.expand`

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

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

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

Load a into reg64

reg63 = reg64 + 1

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RTL for i386: Arithmetic Operations (2)

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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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.144r.expand`

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

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

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

Load a into reg64

reg63 = reg64 + 1

store reg63 into a

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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RTL for i386: Arithmetic Operations (2)

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.144r.expand`

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

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

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


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RTL for i386: Arithmetic Operations (2)

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.144r.expand`

```
(insn 10 9 11 4 (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))
  ]) t1.c:25 -1 (nil))
```


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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.144r.expand`

```
(insn 10 9 11 4 (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))
  ]) t1.c:25 -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

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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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.144r.expand`

```
(insn 10 9 11 4 (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))
  ]) t1.c:25 -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;
}
```

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

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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.144r.expand`

```
(insn 10 9 11 4 (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))
 ]) t1.c:25 -1 (nil))
```


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RTL for i386: Arithmetic Operation (4)

Notes

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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.144r.expand`

```
(insn 10 9 11 4 (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))
 ]) t1.c:25 -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;
}
```

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RTL for i386: Arithmetic Operation (4)

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

RTL for spim: Arithmetic Operations

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

Dump file: `test.c.144r.expand`

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

```
(insn 7 6 8 4 (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)) test.c:6 -1 (nil))
```

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

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RTL for spim: Arithmetic Operations

Notes

RTL for i386: Control Flow

What does this represent?

```
(jump_insn 15 14 16 4 (set (pc)
     (if_then_else (lt (reg:CCGC 17 flags)
         (const_int 0 [0x0]))
       (label_ref 12)
       (pc))) p1.c:6 -1 (nil)
     (nil)
   -> 12)
```

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

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RTL for i386: Control Flow

Notes

RTL for i386: Control Flow

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

Dump file: `test.c.144r.expand`

```
(insn 8 7 9 (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])) test.c:7 -1 (nil))
(insn 9 8 10 (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]))) test.c:7 -1 (nil))
(jump_insn 10 9 0 (set (pc)
    (if_then_else (le (reg:CCGC 17 flags)
        (const_int 0 [0x0]))
        (label_ref 13)
        (pc))) test.c:7 -1 (nil)
       -> 13)
```


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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.188r.asmcons`

(observable dump before register allocation)

```
(insn 10 9 11 3 (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  (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 test.c:5 (nil))

(insn 12 11 22 3  (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_internal test.c:5 (nil))
```


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Observing Register Allocation for i386

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Observing Register Allocation for i386

test.c.188r.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))
```

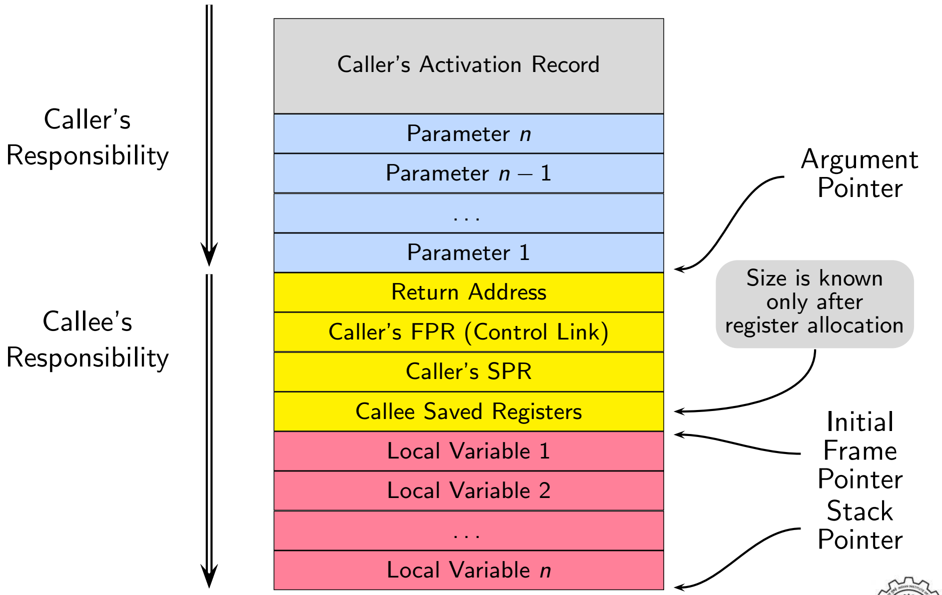
test.c.188r.ira

```
(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]))
```


Observing Register Allocation for i386

Notes

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

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RTL for Function Calls in spim

Notes

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Prologue and Epilogue: spim

Dump file: `test.c.197r.pro_and_epilogue`

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

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


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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
        addl  %edx, %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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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
        addl  %edx, %eax
        addl  -12(%ebp), %eax
        movl  %eax, -4(%ebp)
.L6:
```

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


i386 Assembly

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
        addl  %edx, %eax
        addl  -12(%ebp), %eax
        movl  %eax, -4(%ebp)
.L6:
```

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


i386 Assembly

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
        addl  %edx, %eax
        addl  -12(%ebp), %eax
        movl  %eax, -4(%ebp)
.L6:
```

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


i386 Assembly

Notes

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 the machine
- 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
```


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Gray Box Probing of GCC: Conclusions

Notes

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