Workshop on Essential Abstractions in GCC

Graybox Probing for Machine Independent Optimizations

GCC Resource Center

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

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

30 June 2011

Outline

- Example 1
  - Constant Propagation
  - Copy Propagation
  - Dead Code Elimination
  - Loop unrolling
- Example 2
  - Partial Redundancy Elimination
  - Copy Propagation
  - Dead Code Elimination

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Outline

Notes

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Part 1

First Example Program

Example Program 1

```
int main()
{ int a, b, c, n;

  a = 1;
  b = 2;
  c = 3;
  n = c*2;
  while (a <= n)
  {
    a = a+1;
  }
  if (a < 12)
    a = a+b+c;
  return a;
}
```

- What does this program return?
- 12
- We use this program to illustrate various shades of the following optimizations:
  Constant propagation, Copy propagation, Loop unrolling, Dead code elimination

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Example Program 1

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Compilation Command

```
$gcc -fdump-tree-all  -O2 ccp.c
```

Notes

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Compilation Command

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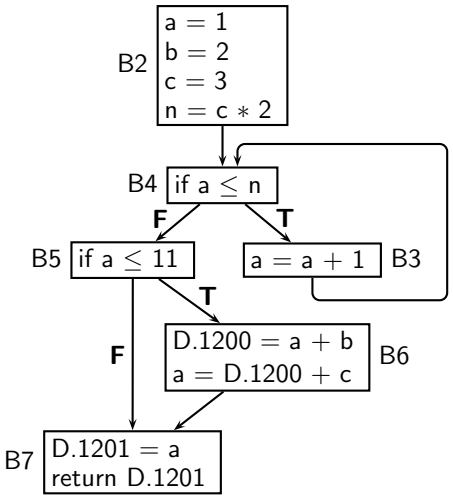
Example Program 1

Program ccp.c

```
int main()
{ int a, b, c, n;

  a = 1;
  b = 2;
  c = 3;
  n = c*2;
  while (a <= n)
  {
    a = a+1;
  }
  if (a < 12)
    a = a+b+c;
  return a;
}
```

Control flow graph



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Example Program 1

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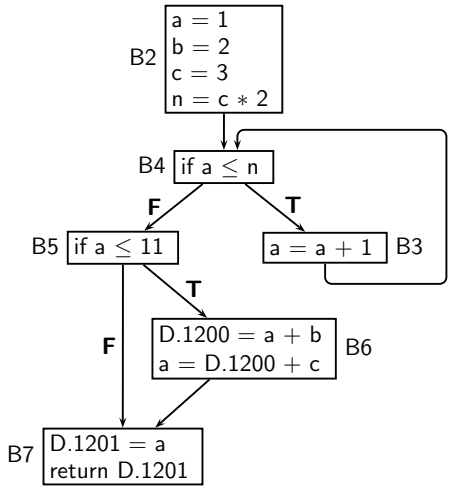
Control Flow Graph: Pictorial and Textual View

Control flow graph



Dump file ccp.c.013t.cfg

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Control Flow Graph: Pictorial and Textual View

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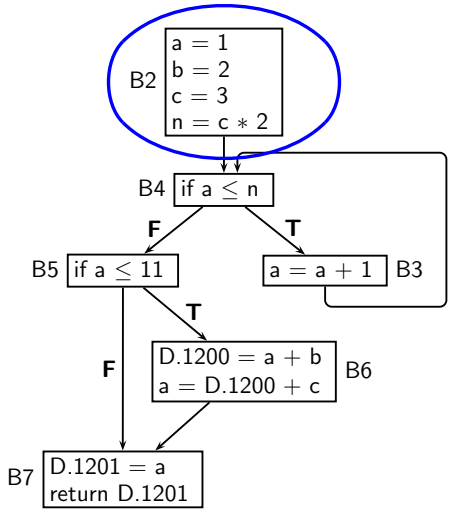
Control Flow Graph: Pictorial and Textual View

Control flow graph



Dump file ccp.c.013t.cfg

```
<bb 2>:
a = 1;
b = 2;
c = 3;
n = c * 2;
goto <bb 4>;
```

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Control Flow Graph: Pictorial and Textual View

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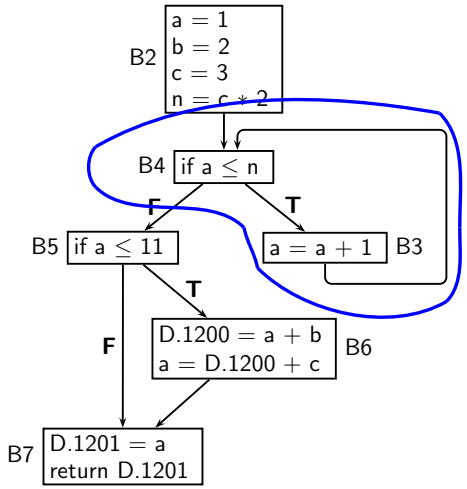
Control Flow Graph: Pictorial and Textual View

Control flow graph



Dump file ccp.c.013t.cfg

```
<bb 3>:
a = a + 1;

<bb 4>:
if (a <= n)
   goto <bb 3>;
else
   goto <bb 5>;
```

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Control Flow Graph: Pictorial and Textual View

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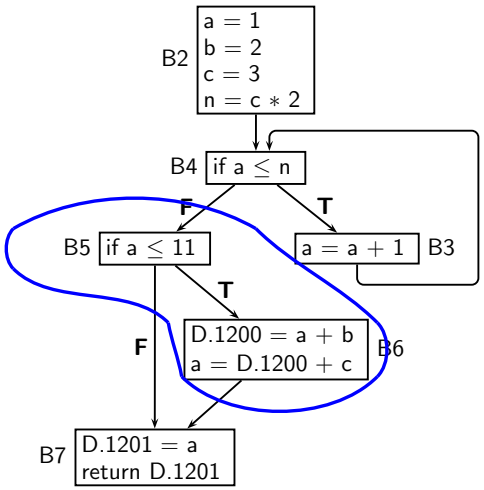
Control Flow Graph: Pictorial and Textual View

Control flow graph



Dump file ccp.c.013t.cfg

```
<bb 5>:
if (a <= 11)
    goto <bb 6>;
else
    goto <bb 7>;

<bb 6>:
D.1200 = a + b;
a = D.1200 + c;
```

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Control Flow Graph: Pictorial and Textual View

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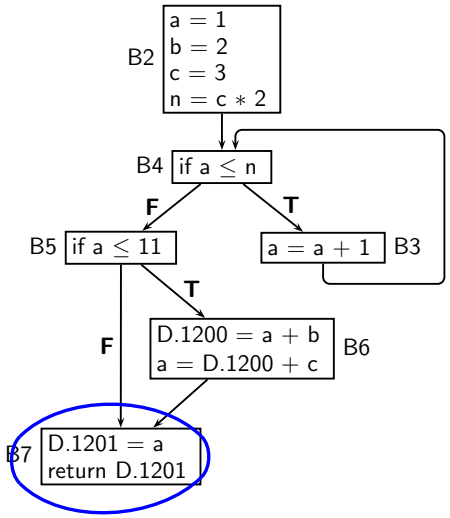
Control Flow Graph: Pictorial and Textual View

Control flow graph



Dump file ccp.c.013t.cfg

```
<bb 7>:
D.1201 = a;
return D.1201;
```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Control Flow Graph: Pictorial and Textual View

Notes

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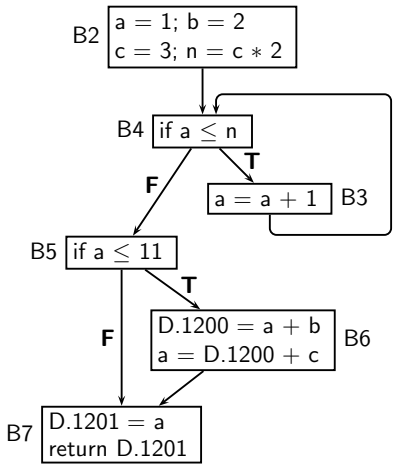
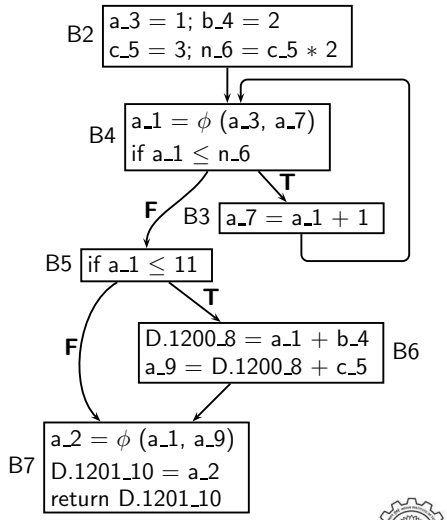
Single Static Assignment (SSA) Form

Control flow graph



SSA Form



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Single Static Assignment (SSA) Form

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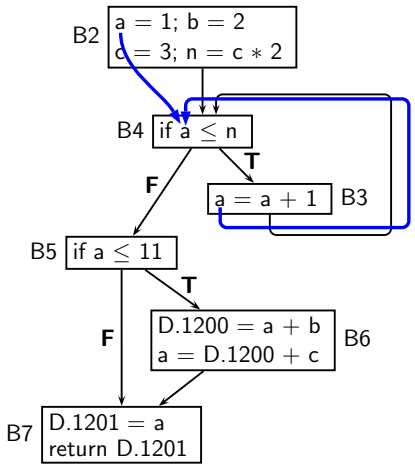
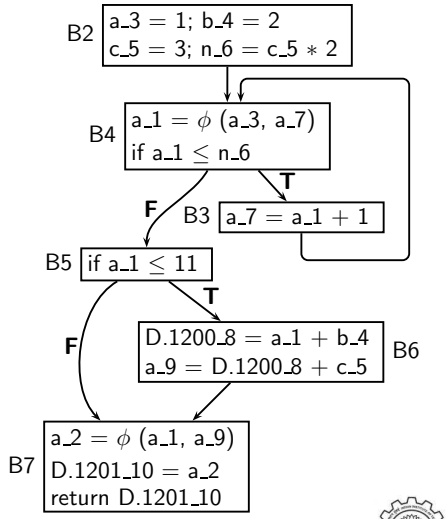
Single Static Assignment (SSA) Form

Control flow graph



SSA Form



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Single Static Assignment (SSA) Form

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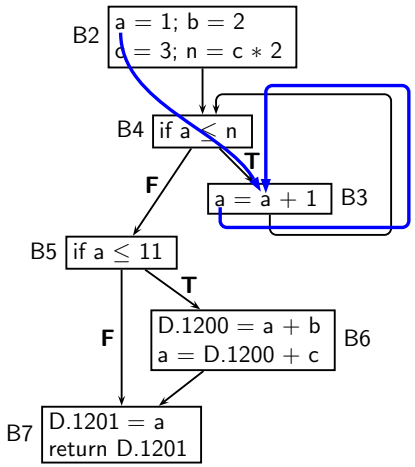
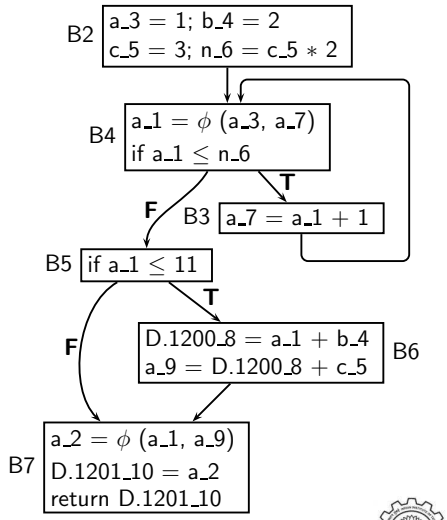
Single Static Assignment (SSA) Form

Control flow graph



SSA Form



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Single Static Assignment (SSA) Form

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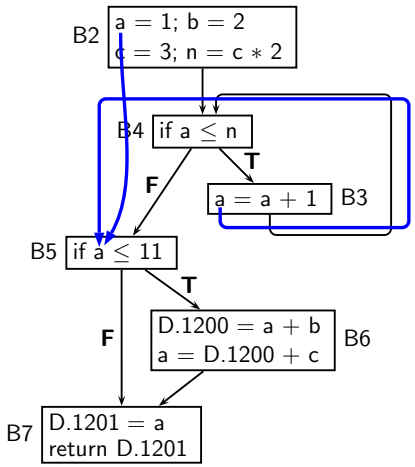
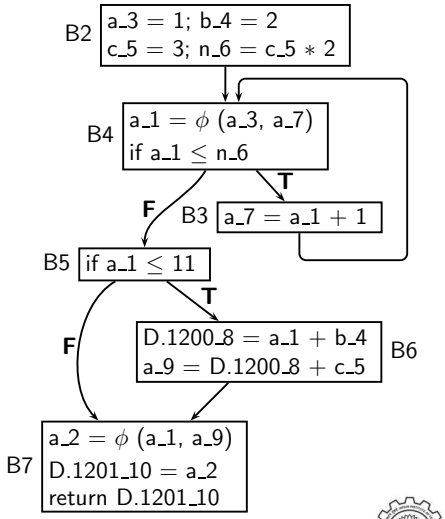
Single Static Assignment (SSA) Form

Control flow graph



SSA Form



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Single Static Assignment (SSA) Form

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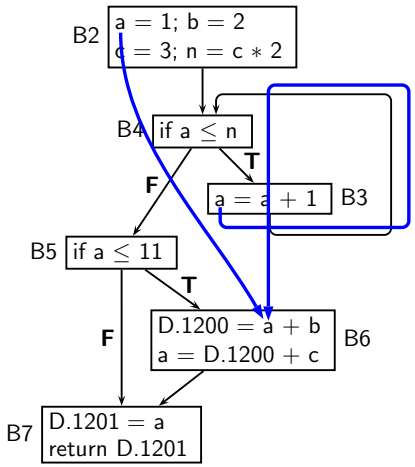
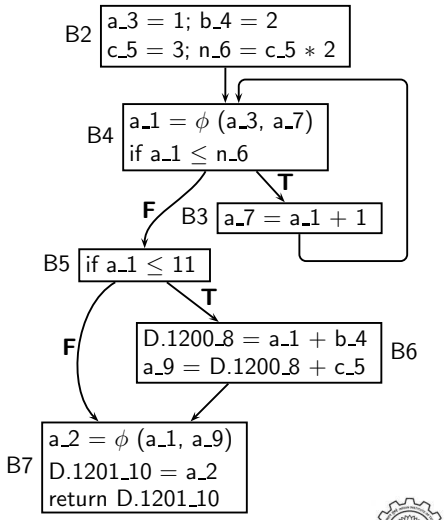
Single Static Assignment (SSA) Form

Control flow graph



SSA Form



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Single Static Assignment (SSA) Form

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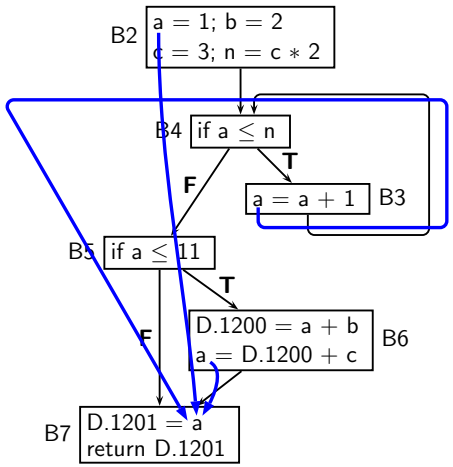
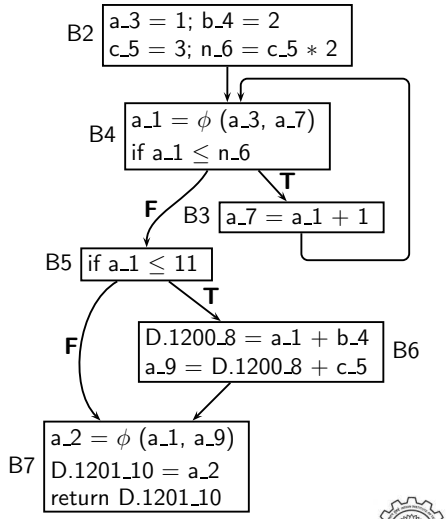
Single Static Assignment (SSA) Form

Control flow graph



SSA Form



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Single Static Assignment (SSA) Form

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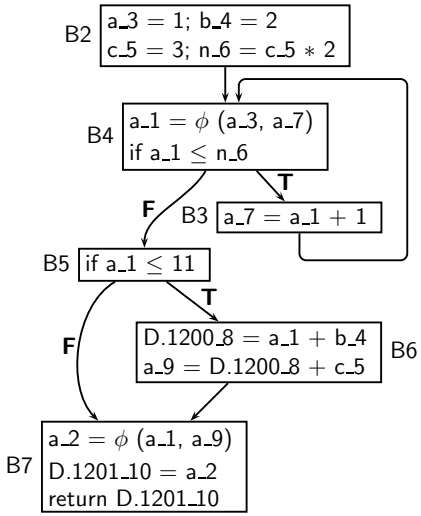
Properties of SSA Form



- A ϕ function is a multiplexer or a selection function
- Every use of a variable corresponds to a unique definition of the variable
- For every use, the definition is guaranteed to appear on every path leading to the use

SSA construction algorithm is expected to insert as few ϕ functions as possible to ensure the above properties

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Properties of SSA Form

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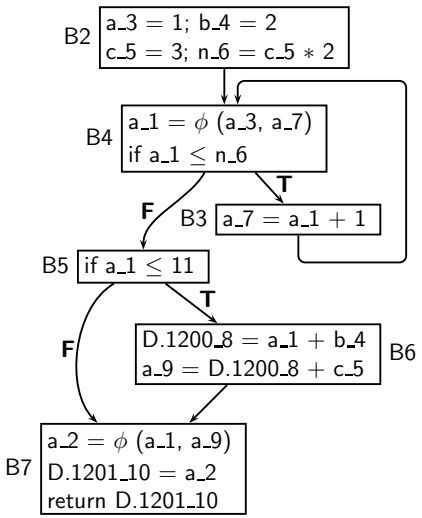
SSA Form: Pictorial and Textual View

CFG in SSA form



Dump file ccp.c.017t.ssa

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SSA Form: Pictorial and Textual View

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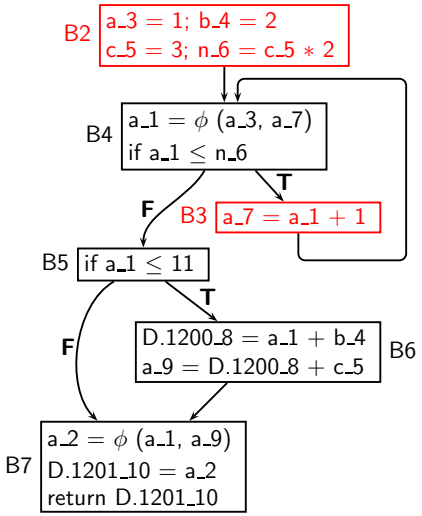
SSA Form: Pictorial and Textual View

CFG in SSA form



Dump file ccp.c.017t.ssa

```
<bb 2>:
  a_3 = 1;
  b_4 = 2;
  c_5 = 3;
  n_6 = c_5 * 2;
  goto <bb 4>;

<bb 3>:
  a_7 = a_1 + 1;
```

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SSA Form: Pictorial and Textual View

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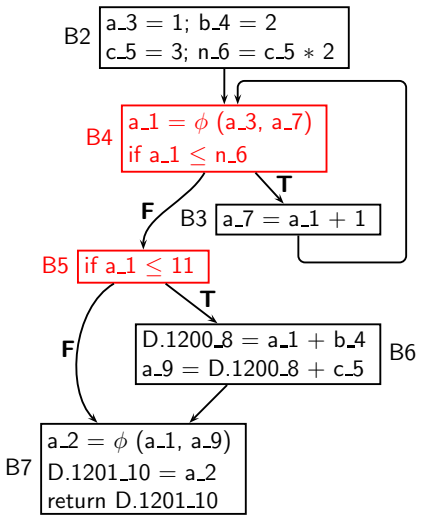
SSA Form: Pictorial and Textual View

CFG in SSA form



Dump file ccp.c.017t.ssa

```
<bb 4>:
  # a_1 = PHI <a_3(2), a_7(3)>
  if (a_1 <= n_6)
    goto <bb 3>;
  else
    goto <bb 5>;

<bb 5>:
  if (a_1 <= 11)
    goto <bb 6>;
  else
    goto <bb 7>;
```

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SSA Form: Pictorial and Textual View

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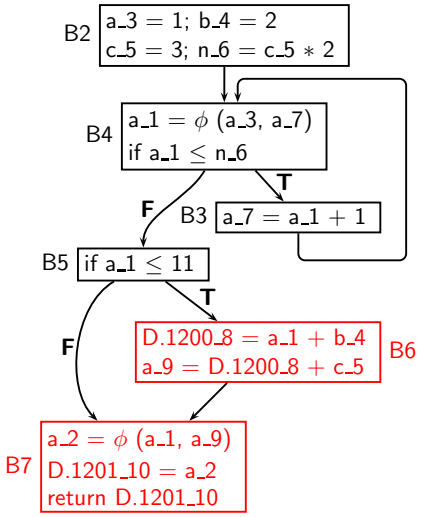
SSA Form: Pictorial and Textual View

CFG in SSA form



Dump file ccp.c.017t.ssa

```
<bb 6>:
  D.1200_8 = a_1 + b_4;
  a_9 = D.1200_8 + c_5;

<bb 7>:
  # a_2 = PHI <a_1(5), a_9(6)>
  D.1201_10 = a_2;
  return D.1201_10;
```

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SSA Form: Pictorial and Textual View

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A Comparison of CFG and SSA Dumps

Dump file ccp.c.013t.cfg

```
<bb 2>:
  a = 1;
  b = 2;
  c = 3;
  n = c * 2;
  goto <bb 4>;

<bb 3>:
  a = a + 1;
```

Dump file ccp.c.017t.ssa

```
<bb 2>:
  a_3 = 1;
  b_4 = 2;
  c_5 = 3;
  n_6 = c_5 * 2;
  goto <bb 4>;

<bb 3>:
  a_7 = a_1 + 1;
```

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A Comparison of CFG and SSA Dumps

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A Comparison of CFG and SSA Dumps

Dump file ccp.c.013t.cfg

```
<bb 4>:
  if (a <= n)
     goto <bb 3>;
  else
     goto <bb 5>;

<bb 5>:
  if (a <= 11)
      goto <bb 6>;
  else
      goto <bb 7>;
```

Dump file ccp.c.017t.ssa

```
<bb 4>:
  # a_1 = PHI <a_3(2), a_7(3)>
  if (a_1 <= n_6)
    goto <bb 3>;
  else
    goto <bb 5>;

<bb 5>:
  if (a_1 <= 11)
    goto <bb 6>;
  else
    goto <bb 7>;
```

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A Comparison of CFG and SSA Dumps

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A Comparison of CFG and SSA Dumps

Dump file ccp.c.013t.cfg

```
<bb 6>:
D.1200 = a + b;
a = D.1200 + c;

<bb 7>:
D.1201 = a;
return D.1201;
```

Dump file ccp.c.017t.ssa

```
<bb 6>:
  D.1200_8 = a_1 + b_4;
  a_9 = D.1200_8 + c_5;

<bb 7>:
  # a_2 = PHI <a_1(5), a_9(6)>
  D.1201_10 = a_2;
  return D.1201_10;
```

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A Comparison of CFG and SSA Dumps

Notes

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Copy Renamimg

Input dump: ccp.c.017t.ssa

```
<bb 7>:
  # a_2 = PHI <a_1(5), a_9(6)>
  D.1201_10 = a_2;
  return D.1201_10;
```

Output dump: ccp.c.022t.copyrename1

```
<bb 7>:
  # a_2 = PHI <a_1(5), a_9(6)>
  a_10 = a_2;
  return a_10;
```

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Copy Renamimg

Notes

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First Level Constant and Copy Propagation

Input dump: ccp.c.022t.copyrename1

```
<bb 2>:
  a_3 = 1;
  b_4 = 2;
  c_5 = 3;
  n_6 = c_5 * 2;
  goto <bb 4>;

<bb 3>:
  a_7 = a_1 + 1;

<bb 4>:
  # a_1 = PHI < a_3(2), a_7(3)>
  if (a_1 <= n_6)
    goto <bb 3>;
  else
    goto <bb 5>;
```

Output dump: ccp.c.023t.ccp1

```
<bb 2>:
  a_3 = 1;
  b_4 = 2;
  c_5 = 3;
  n_6 = 6;
  goto <bb 4>;

<bb 3>:
  a_7 = a_1 + 1;

<bb 4>:
  # a_1 = PHI < 1(2), a_7(3)>
  if (a_1 <= 6)
    goto <bb 3>;
  else
    goto <bb 5>;
```

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First Level Constant and Copy Propagation

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First Level Constant and Copy Propagation

Input dump: ccp.c.022t.copyrename1

```
<bb 2>:
  a_3 = 1;
  b_4 = 2;
  c_5 = 3;
  n_6 = 6;
  goto <bb 4>;

...

<bb 6>:
  D.1200_8 = a_1 + b_4;
  a_9 = D.1200_8 + c_5;
```

Output dump: ccp.c.023t.ccp1

```
<bb 2>:
  a_3 = 1;
  b_4 = 2;
  c_5 = 3;
  n_6 = 6;
  goto <bb 4>;

 ...

<bb 6>:
  D.1200_8 = a_1 + 2;
  a_9 = D.1200_8 + 3;
```

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First Level Constant and Copy Propagation

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Second Level Copy Propagation

Input dump: ccp.c.023t.ccp1

```
<bb 6>:
  D.1200_8 = a_1 + 2;
  a_9 = D.1200_8 + 3;

<bb 7>:
  # a_2 = PHI <a_1(5), a_9(6)>
  a_10 = a_2;
  return a_10;
```

Output dump: ccp.c.027t.copyprop1

```
<bb 6>:
  a_9 = a_1 + 5;

<bb 7>:
  # a_2 = PHI <a_1(5), a_9(6)>
  return a_2;
```

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Second Level Copy Propagation

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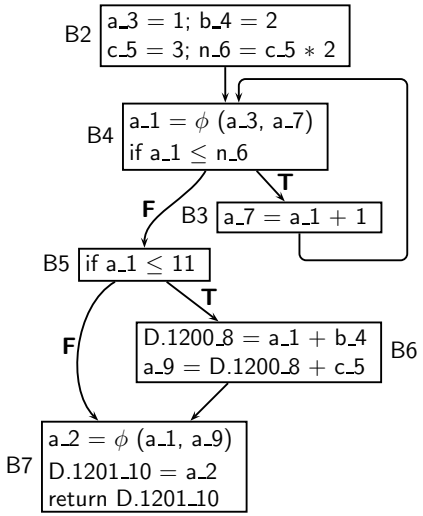
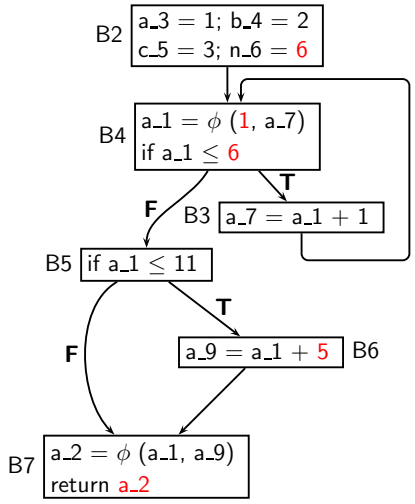
The Result of Copy Propagation and Renaming





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The Result of Copy Propagation and Renaming

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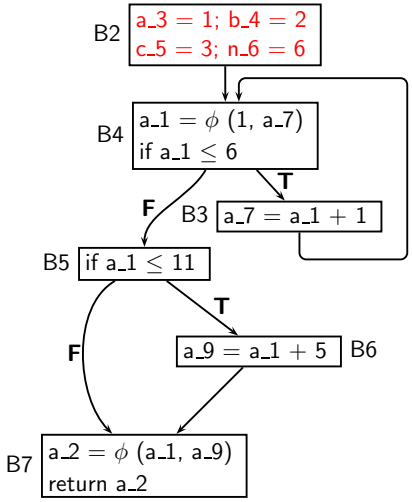
The Result of Copy Propagation and Renaming



- No uses for variables a_3, b_4, c_5, and n_6
- Assignments to these variables can be deleted

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The Result of Copy Propagation and Renaming

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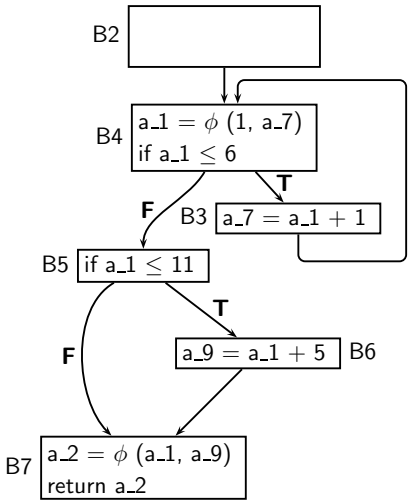
Dead Code Elimination Using Control Dependence



Dump file ccp.c.029t.cddce1

```
<bb 2>:
  goto <bb 4>;
<bb 3>:
  a_7 = a_1 + 1;
<bb 4>:
  # a_1 = PHI <1(2), a_7(3)>
  if (a_1 <= 6) goto <bb 3>;
  else goto <bb 5>;
<bb 5>:
  if (a_1 <= 11) goto <bb 6>;
  else goto <bb 7>;
<bb 6>:
  a_9 = a_1 + 5;
<bb 7>:
  # a_2 = PHI <a_1(5), a_9(6)>
  return a_2;
```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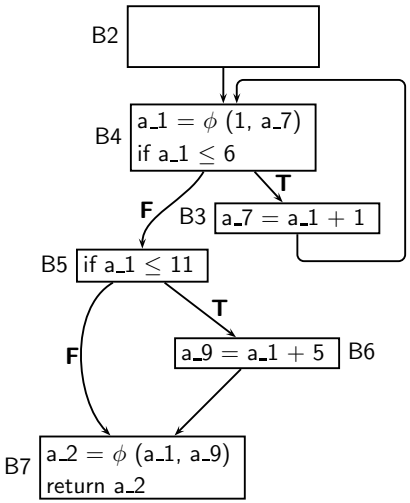
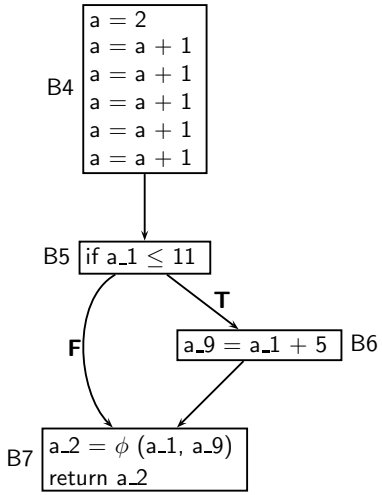
Dead Code Elimination Using Control Dependence

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Loop Unrolling





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Loop Unrolling

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

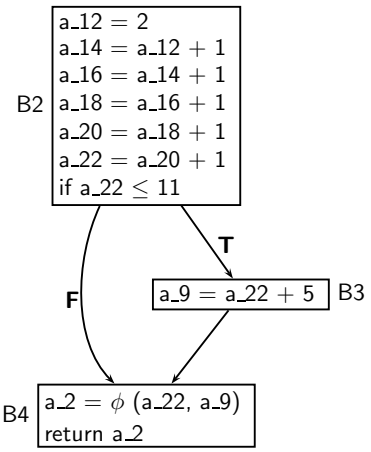
Complete Unrolling of Inner Loops

Dump file: ccp.c.058t.cunrolli

```
<bb 2>:
  a_12 = 2;
  a_14 = a_12 + 1;
  a_16 = a_14 + 1;
  a_18 = a_16 + 1;
  a_20 = a_18 + 1;
  a_22 = a_20 + 1;
  if (a_22 <= 11) goto <bb 3>;
  else goto <bb 4>;

<bb 3>:
  a_9 = a_22 + 5;

<bb 4>:
  # a_2 = PHI <a_22(2), a_9(3)>
  return a_2;
```



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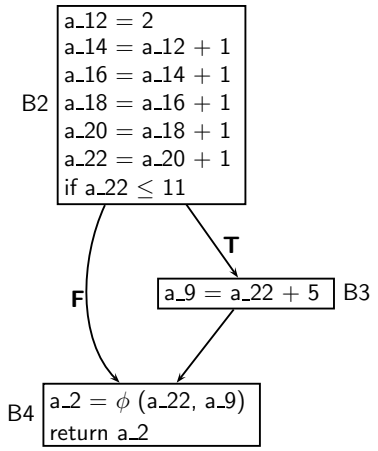
Complete Unrolling of Inner Loops

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Another Round of Constant Propagation

Input



Dump file: ccp.c.059t.ccp2

```
main ()
{
  <bb 2>:
    return 12;

}
```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Another Round of Constant Propagation

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Part 2

Second Example Program

Example Program 2

```
int f(int b, int c, int n)
{ int a;

   do
   {
      a = b+c;
   }
   while (a <= n);

   return a;
}
```

We use this program to illustrate the following optimizations:

Partial Redundancy Elimination, Copy Propagation, Dead Code Elimination

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Example Program 2

Notes

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Compilation Command

```
$gcc -fdump-tree-all  -O2 -S ccp.c
```

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Compilation Command

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Example Program 2

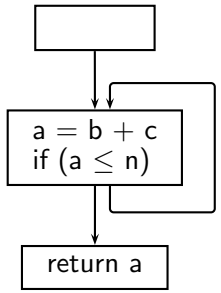
loop.c

```
int f(int b, int c, int n)
{ int a;

   do
   {
      a = b+c;
   }
   while (a <= n);

   return a;
}
```

Control Flow Graph



Notes

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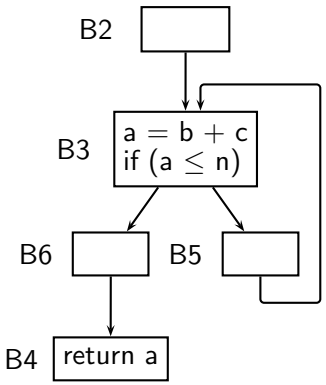
Example Program 2

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Dump of Input to PRE Pass

Control Flow Graph



loop.c.091t.crited

```
<bb 2>:

<bb 3>:
  a_3 = b_1(D) + c_2(D);
  if (a_3 <= n_4(D)) goto <bb 5>;
  else goto <bb 6>;

<bb 5>:
  goto <bb 3>;

<bb 6>:

<bb 4>:
  # a_6 = PHI <a_3(6)>
  return a_6;
```


Notes

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Dump of Input to PRE Pass

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Input and Output of PRE Pass

loop.c.091t.crited

```
<bb 2>:

<bb 3>:
  a_3 = b_1(D) + c_2(D);
  if (a_3 <= n_4(D))
       goto <bb 5>;
  else goto <bb 6>;

<bb 5>:
  goto <bb 3>;

<bb 6>:
<bb 4>:
  # a_6 = PHI <a_3(6)>
  return a_6;
```

loop.c.092t.pre

```
<bb 2>:
  pretmp.2_7 = b_1(D) + c_2(D);

<bb 3>:
  a_3 = pretmp.2_7;
  if (a_3 <= n_4(D))
       goto <bb 5>;
  else goto <bb 6>;

<bb 5>:
  goto <bb 3>;

<bb 6>:
<bb 4>:
  # a_6 = PHI <a_3(6)>
  return a_6;
```

Notes

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Input and Output of PRE Pass

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Copy Propagation after PRE

loop.c.092t.pre

```
<bb 2>:
  pretmp.2_7 = b_1(D) + c_2(D);

<bb 3>:
  a_3 = pretmp.2_7;
  if ( a_3 <= n_4(D))
       goto <bb 5>;
  else goto <bb 6>;

<bb 5>:
  goto <bb 3>;

<bb 6>:
<bb 4>:
  # a_6 = PHI <a_3(6)>
  return a_6;
```

loop.c.097t.copyprop4

```
<bb 2>:
  pretmp.2_7 = b_1(D) + c_2(D);

<bb 3>:
  a_3 = pretmp.2_7;
  if ( n_4(D) >= pretmp.2_7)
    goto <bb 4>;
  else
    goto <bb 5>;

<bb 4>:
  goto <bb 3>;

<bb 5>:
  # a_8 = PHI <pretmp.2_7(3)>
  a_6 = a_8;
  return a_8;
```

Notes

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Copy Propagation after PRE

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Dead Code Elimination

loop.c.097t.copyprop4

```
<bb 2>:
  pretmp.2_7 = b_1(D) + c_2(D);

<bb 3>:
  a_3 = pretmp.2_7;
  if (n_4(D) >= pretmp.2_7)
    goto <bb 4>;
  else
    goto <bb 5>;

<bb 4>:
  goto <bb 3>;

<bb 5>:
  # a_8 = PHI <pretmp.2_7(3)>
  a_6 = a_8;
  return a_8;
```

loop.c.098t.dceloop1

```
<bb 2>:
  pretmp.2_7 = b_1(D) + c_2(D);

<bb 3>:
  if (n_4(D) >= pretmp.2_7)
    goto <bb 4>;
  else
    goto <bb 5>;

<bb 4>:
  goto <bb 3>;

<bb 5>:
  # a_8 = PHI <pretmp.2_7(3)>
  return a_8;
```

Dead Code Elimination

Notes

Redundant ϕ Function Elimination and Copy Propagation

loop.c.098t.dceloop1

```
<bb 2>:
  pretmp.2_7 = b_1(D) + c_2(D);

<bb 3>:
  if (n_4(D) >= pretmp.2_7)
    goto <bb 4>;
  else
    goto <bb 5>;

<bb 4>:
  goto <bb 3>;

<bb 5>:
  # a_8 = PHI <pretmp.2_7(3)>
  return a_8;
```

loop.c.125t.phicprop2

```
<bb 2>:
  pretmp.2_7 = c_2(D) + b_1(D);
  if (n_4(D) >= pretmp.2_7)
    goto <bb 4>;
  else
    goto <bb 3>;

<bb 3>:
  return pretmp.2_7;

<bb 4>:
  goto <bb 4>;
```

Redundant ϕ Function Elimination and Copy Propagation

Notes

Final Assembly Program

loop.c.125t.phicprop2

```
<bb 2>:
  pretmp.2_7 = c_2(D) + b_1(D);
  if (n_4(D) >= pretmp.2_7)
    goto <bb 4>;
  else
    goto <bb 3>;

<bb 3>:
  return pretmp.2_7;

<bb 4>:
  goto <bb 4>;
```

loop.s

```
    movl    8(%esp), %eax
    addl    4(%esp), %eax
    cmpl    %eax, 12(%esp)
    jge     .L2
    rep
    ret
.L2:
.L3:
    jmp     .L3
```

Why infinite loop?

Notes

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Final Assembly Program

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Infinite Loop in Example Program 2

```
int f(int b, int c, int n)
{ int a;

   do
   {
      a = b+c;
   }
   while (a <= n);

   return a;
}
```

The program does not terminate unless a $>$ n

Notes

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Infinite Loop in Example Program 2

Essential Abstractions in GCC GCC Resource Center, IIT Bombay

Part 3

Conclusions

Conclusions

- GCC performs many machine independent optimizations
- The dumps of optimizations are easy to follow, particularly at the GIMPLE level
- It is easy to prepare interesting test cases and observe the effect of transformations
- One optimization often leads to another
  Hence GCC performs many optimizations repeatedly
  (eg. copy propagation, dead code elimination)

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Conclusions

Notes

Essential Abstractions in GCC GCC Resource Center, IIT Bombay